

PB-230 539

PROJECT FOR CONCENTRATED RESEARCH
AND TRAINING IN THE HYDRAULIC AND
HYDROLOGIC ASPECTS OF WATER
POLLUTION CONTROL

Peter A. Krenkel, et al

National Center for Research and Training
in the Hydrologic and Hydraulic Aspects
of Water Pollution Control

Prepared for:

Federal Water Pollution Control Administration

October 1969

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

Project for Concentrated Research and
Training in the Hydraulic and Hydrologic
Aspects of Water Pollution Control

PROGRESS REPORT

1 August 1968 — 1 September 1969

PETER A. KRENKEL

FRANK L. PARKER

Co-Directors



National Center For Research and Training in the
Hydrologic and Hydraulic Aspects of Water Pollution Control

REPORT NUMBER 2

Department of Environmental & Water Resources Engineering

Vanderbilt University

School of Engineering

Nashville, Tennessee

October 1969

ACKNOWLEDGEMENTS

The work described herein was supported by the Federal Water Pollution Control Administration under Research Grant #WP-O 1463-01A1. The Grant has established a National Center for Research and Training in the Hydrologic and Hydraulic Aspects of Water Pollution Control within the Department of Environmental and Water Resources Engineering at Vanderbilt University. This report represents the second in a series of research reports to be published by the Center under the co-direction of Dr. Peter A. Krenkel and Dr. Frank L. Parker.

The authors would like to acknowledge the cooperation and aid of the Tennessee Valley Authority in making possible the collection of much of the data presented herein.

TABLE OF CONTENTS

PROJECT FOR CONCENTRATED RESEARCH AND TRAINING IN THE HYDROLOGIC AND HYDRAULIC ASPECTS OF WATER POLLUTION CONTROL	1
Organization	1
ACTIVITIES	5
Directly Related to Center	5
Activities Indirectly Related to Center	7
EDUCATION AND TRAINING ASPECTS OF CENTER	12
Graduates During Year	12
Current Research Projects	15
Current Educational Program	16
RESEARCH ACCOMPLISHMENTS	17
Temperature Distributions Resulting from Cooling water Discharges	17
Heated Surface Jets Discharged into a Flowing Ambient Stream	44
Effect of Geographical Location on Cooling Pond Requirements and Performance	72
Status of the Art and Research Needs for Thermal Pollution	113
Initial Mixing of Thermal Discharges into a Uniform Current	115
RESEARCH ACCOMPLISHMENTS (PROJECTS NOT SUPPORTED BY GRANT FUNDS	116
Negative Buoyant Jets in Flowing Streams	116
Water Quality Changes in a Newly Constructed Reservoir	120
Immobilization of Phosphorus in Bottom Sediments	122
Quantifying the Effects of Rate of Temperature Change on the Biota	126

PROPOSED WORK	136
Introduction	136
Temperature Distributions Resulting From	
Cooling Water Discharges	137
Effect of Geographical Location on Cooling Pond	
Requirements and Performance	140
Discharge of Negatively Buoyant Fluids	142
Temperature Increases Below Dams	145
Heat Transfer in Flowing Waters	147
Separation of Solar and Heated Discharge Effects	150
Mass and Heat Transfer Across Density	
Discontinuities	152



PROJECT FOR CONCENTRATED RESEARCH AND TRAINING IN THE HYDROLOGIC
AND HYDRAULIC ASPECTS OF WATER POLLUTION CONTROL

Progress Report: 1 August 1968 - 1 September 1969

Peter A. Krenkel

Frank L. Parker

ORGANIZATION

Introduction

A major deficiency in the water pollution control field presently exists in both training and research activities into the many water quality problems directly affected by the hydraulics and hydrology of the receiving stream. This is evidenced by the many requests by regulatory agencies, industry and consulting engineers for personnel trained in hydrology and hydraulics but with a sound background in water quality control. For this reason, and because of the paucity of similar opportunities elsewhere, our training and research has been oriented toward this area. Our engineering faculty are all specifically trained and research-oriented toward the hydraulic and hydrologic aspects of water pollution control. The graduates that we produce not only have a sound background in the unit operations and processes of sanitary engineering, but are well grounded in hydraulics, hydrology, fluid mechanics, and the

associated physical sciences and mathematics required to work in the field of water pollution control. We especially emphasize the practical applications of the principles learned in the classroom with particular reference to the problems faced in the Tennessee Valley. Because of the close cooperation of the Tennessee Valley Authority personnel, we have been able to use actual data and solutions from their work in the classroom, and some of our research is directed toward solving some of the problems faced by the TVA.

This project is oriented towards alleviating the shortage of competent engineers in this area of endeavor and concentrating on research projects that will produce much needed water quality information for Water Resource Engineers.

Specific Objectives

The specific objectives of this grant are as follows:

1. The formal establishment of a training and research center for hydraulic and hydrologic aspects of water quality control.
2. Continuation of existing research investigations and instigation of new research endeavors in the hydraulic and hydrologic disciplines by adding personnel, including scientists and engineers from the Federal Water Pollution Control Administration assigned to the center, to work for solutions of water quality problems.
3. The establishment of an information retrieval center, which would contain a comprehensive collection of works pertaining to research in this area, and would be available for use by investigators and regulatory agencies throughout the world.

4. The construction of a building to house a center which would contain adequate analytical facilities, model tanks and flumes and hydraulic appurtances, and office space to house the staff.
5. The expansion of the existing training program with additional faculty and students specifically trained in the hydraulic and hydrologic aspects of water pollution control.
6. The establishment of a coordinating committee from Vanderbilt University and the FWPCA to assist and coordinate the activities of the center in accordance with the objectives and programs of both the Department of the Interior and the University.

The objectives, as stated, are, of course, long term goals rather than immediate requirements; however, certain of these objectives have already been accomplished.

Co-ordinating Committee

In order to assure efficient attainment of the ultimate goals of the center, a co-ordinating committee, consisting of personnel from both the Federal Water Pollution Control Administration and Vanderbilt University was formed.

This committee, which has met both formally and informally during the past year, consists of the following members:

William A. Cawley, FWPCA

Frank Rainwater, FWPCA

Donald Baumgartner, FWPCA

Frank L. Parker, Vanderbilt University

Peter A. Krenkel, Vanderbilt University

Robert S. Rowe, Vanderbilt University.

Personnel Directly Involved in Center

The center is under the immediate direction of Peter A. Krenkel and Frank L. Parker, co-directors, and all activities are under their supervision. The field engineer is Mr. Edward Polk, formerly with the Tennessee Stream Pollution Control Board.

Specific projects are under the immediate supervision of Professors Barry A. Benedict, Peter A. Krenkel, Frank L. Parker, Karl B. Schnelle, and Edward L. Thackston. When appropriate, these people, in turn, report to the project co-directors.

Other personnel engaged in project work include abstracters, secretaries, technicians and research assistants, which may be supported by other funds.

ACTIVITIES

DIRECTLY RELATED TO CENTER

Thermal Pollution Symposia - One of the major efforts under the center grant is to broaden our knowledge of the effects and means of alleviating thermal pollution. To determine the present state of knowledge in the field, Vanderbilt University and the Federal Water Pollution Control Administration cosponsored two symposia on thermal pollution. The first symposium on the Biological Aspects of Thermal Pollution was held at Portland, Oregon on June 3 to 5, 1968. The engineering aspects of the problem were introduced to the participants, and then a series of papers by the foremost workers in the field was presented. This brought together in one place the biological information available today and listed the research needs. Since ample time was allowed for discussion, a good cross-fertilization of ideas took place. The papers were deemed to be of sufficient value that Vanderbilt University Press is publishing the proceedings under the title Biological Aspects of Thermal Pollution - Krenkel and Parker, Editors. Publication is expected late in 1969.

The Engineering and Economic Aspects of Thermal Pollution were discussed at a second symposium held at Vanderbilt University on August 14 to 16, 1968. After an introductory paper on the biological problems, the sessions dealt in depth with the engineering, means, and costs of alleviating thermal pollution. The exposition of cooling tower experience in the United States is perhaps unique. The need for such information is so great that Vanderbilt University Press is publishing the proceedings under the title

Engineering Aspects of Thermal Pollution, Parker and Krenkel, Editors.

Publication is expected late in 1969.

Water Resources Scientific Information Center

During the year, agreement was reached to fund an abstracting service on thermal pollution through the center grant for the Office of Water Resources Research's Water Resources Scientific Information Center. Abstract preparations began during the summer of 1969 with an initial submission of approximately 25 abstracts. The number of abstracts submitted will increase to fifty per month by October, 1969. A wide variety of domestic and foreign journals are scanned to find articles of suitable content. Translations are prepared of those articles deemed of sufficient value.

Information Retrieval System

In the course of preparation of the state of art in thermal pollution and in preparation of the abstracts for the Water Resources Scientific Information Center, a wide variety of material on thermal pollution has been collected. This material is on file in both index cards, filed by author and date of accession, and full size. Copies of material on file can be provided for a nominal fee. It is planned during the course of the study to make this the most comprehensive library and document collections on thermal pollution in the nation.

Microfilm

Due to the large amount of space required for a full size document collection, it has been decided to take advantage of the American Water Resources Association microfilm service of water related journals each

year. Index cards on the individual articles have also been ordered. Over 45,000 pages of water resources literature are then available in convenient form. A reading and reproduction machine for microfilm has been ordered.

ACTIVITIES INDIRECTLY RELATED TO CENTER

Seminar Series

The Department of Environmental and Water Resources Engineering sponsors a weekly seminar series. The cost is paid from funds provided by training grants and the university at no cost to the Research Center.

However, because of the natural interests of the faculty, many of the seminar speakers discuss topics directly related to the work of the Research Center. The seminars thus directly aid the activities of the center by acquainting both faculty, staff, and students with some of the latest ideas and ongoing research being conducted on these subjects.

The seminars are held Tuesday afternoons at 4:00 p.m. Most out-of-town speakers arrive earlier in the day and are provided with a series of appointments with students and staff who wish to discuss individual research or policy questions with him. Topics can be pursued in much greater detail during these informal consultations than time allows during the regular seminar.

The seminar speakers during the period September, 1968 to June, 1969, are tabulated below.

Dr. Frank P. Grisham, Director, Joint Universities Library, Vanderbilt University, 9/26/68, "The Use and Abuse of the Library As a Resource Center".

Mr. Louis Motz, Graduate Student, Vanderbilt University, 10/3/68, "Reaeration by Wind-Driven Circulation".

Mr. Willis H. Lewis, Henshaw, Honeycutt & Lewis, Inc., Nashville, 10/10/68, "The Role of the Consulting Engineer in Environmental Engineering".

Dr. Gerald Berg, Chief of Virology, Cincinnati Water Research Lab, Cincinnati, Ohio, 10/18/68, "The Importance and Fate of Viruses in Waste, Natural and Renovated Waters".

Dr. Joseph M. Bistowish, Director of Health, Metro-Nashville-Davidson County, 10/24/68, "Air Pollution and Air Pollution Ordinances for Nashville, Tennessee".

Mr. S. Leary Jones, Director, Tennessee State Stream Pollution Control Board, Nashville, 10/31/68, "The Who, What, When, Where, and Why of Fish Kills?"

Mr. Frank E. Dalton, Chief Engineer, Metro Sanitary District of Greater Chicago, Illinois, 11/6/68, "Advances in Municipal Water and Sewage Treatment".

Mr. E. Neil Helmers, Manager, Cumberland Regional Office, E. I. DuPont De Nemours & Co., Old Hickory, Tennessee, 11/14/68, "The Water Resources Engineer in the Chemical Industry".

Professor John J. Compton, Chairman, Department of Philosophy, Vanderbilt University, 11/21/68, "Current Issues in the Philosophy of Science".

Mr. David W. Stroh, Associate Chaplain, Vanderbilt University, 12/5/68, "Religion and Science".

Dr. Kay H. Jones, Assistant to the Associate Commissioner for Control Technology Research and Development, National Air Pollution Control Administration, Arlington, Virginia, 12/12/68, "Vehicular Emissions".

Dr. Nicholas Georgescu-Roegen, Professor, Department of Economics and Business Administration, Vanderbilt University, 12/19/68, "Expectation and Uncertainty in Engineering Decisions".

Dr. Thomas Philbin, Environmental Engineer, Niagara Mohawk Power Corporation, Buffalo, New York, 1/7/69, "Environmental Engineering in the Electrical Utility Industry".

Mr. Henry P. Caulfield, Jr., Executive Director, Water Resources Council, Washington, D.C., 1/30/69, "The Water Resources Council and the new Water Commission".

Dr. John Cairns, Jr., Department of Biology, Virginia Polytechnic Institute, Blacksburg, 2/4/69, "Effects of Heat Effluents on Fish".

Mr. Ross Brudenell, Tennessee Valley Authority, Chattanooga, Tennessee, 2/11/69, "Use of a Computer in Scheduling Power Generation on the TVA System".

Dr. Edward Cleary, Professor of Civil Engineering, University of Cincinnati, 3/4/69, "ORSANCO - How it Works".

Mr. Cecil Chambers, Robert A. Taft Sanitary Engineering Center, U.S.P.H.S., Cincinnati, Ohio, 3/18/69, "Germicidal Studies in Water and Waste Treatment".

Mr. Francis Mayo, Director, Division of Planning and Interagency Programs, FWPCA, U. S. Department of the Interior, Washington, D.C., 4/1/69, "The Role of the Federal Water Pollution Control Administration".

Dr. Arthur Stern, Professor of the Department of Environmental Engineering Sciences, University of North Carolina, Chapel Hill, 4/8/69, "Air Pollution".

Dr. Charles Howe, Director of Resources for the Future, Inc., Water Program, Washington, D.C., 4/22/69, "Resources for the Future Studies in Water Resources".

Mr. M. I. Foster, Tennessee Valley Authority, Chattanooga, Tennessee, 4/29/69, "Water Resources Economics at TVA".

Mr. Frank Gifford, U. S. Weather Bureau, City of Oak Ridge, Tennessee, 5/6/69, "Atmospheric Studies".

Environmental and Water Resources Engineering Conference

The Eighth Annual Environmental and Water Resources Engineering Conference was held June 5-6, 1969, sponsored by Vanderbilt University, the Tennessee Department of Public Health, and the Tennessee Stream Pollution Control Board. It was directed by Edward L. Thackston, and the program committee consisted of S. Leary Jones (Executive Secretary of the Tennessee Stream Pollution Control Board) and Edward L. Thackston, Co-Chairmen, Barry A. Benedict, Frank L. Parker, and Karl B. Schnelle.

While the Annual Conference has no direct connection with the Research Center, they are both concerned with the same basic objectives and complement each other. The Conference has been planned to help satisfy the need for exchange and dissemination of information concerning the environmental engineering problems confronting industry, consulting engineers, municipalities and regulatory agencies in our geographical area. The

objectives of the Conference are to bring together all those concerned with environmental and water resources engineering problems, to encourage an exchange of knowledge and experience, and to stimulate research.

The Conference benefits from the presence of the Research Center by making the program committee more cognizant of the critical problems in a particular area and of the best sources of current research and information on them, thus improving the program. The Research Center benefits because the Conference offers a vehicle for attracting to Vanderbilt expert speakers on pertinent subjects, allowing informal consultation with Research Center workers.

Over the past several years, the Conference has traditionally had several speakers on the subjects covered by the objectives of the Research Center. At the last Conference these would include

- (1) Hydraulic Overloading - Fact or Fiction?: James C. North, Vice-President, Resource Consultants, Nashville, Tennessee, and H. D. Tomlinson, Vice-President, Ryckman, Edgerly, Tomlinson, and Associates, St. Louis, Missouri.
- (2) Engineering Problems Encountered in Selective Withdrawal From Multiple - Purpose Reservoirs: Glenn Drummond, Hydraulic Engineer, Reservoir Control Center, Ohio River Division, Corps of Engineers, Cincinnati, Ohio.
- (3) Current Research on Reservoir Destratification: Marvin L. Wood, Director, Robert S. Kerr, Water Research Center, FWPCA, Ada, Oklahoma.
- (4) An Approach to Finding Reservoir Rules for Power Optimization: George K. Young, Senior Engineer, Water Resources Engineers, Walnut Creek, California.

- (5) Some Factors to be Considered in the Design of Waste Disposal Wells: Donald R. Rima, Hydrologist, U. S. Geological Survey, Nashville, Tennessee.

All papers presented at the Conference are printed in the Conference Proceedings. This volume is distributed to many libraries by exchange with the Vanderbilt Library, and sold to many other libraries, agencies, and individuals.

EDUCATION AND TRAINING ASPECTS OF CENTER

The program of the research center is intimately connected with the education and training program of the Department of Environmental and Water Resources Engineering. Both benefit greatly from the presence and activities of the other. For example, the Research Center benefits from having graduate students, supported primarily from other sources, available for part-time work, during summers or on special occasions such as field trips. The Center also benefits by having available the faculty who are primarily concerned with the educational program of the University, but also spend part-time on research for the center. The students benefit from the presence of the Research Center by their contact with a faculty kept up-to-date and active in research by the Center; by having available the library and information retrieval facilities of the Center; and by the availability of research equipment and facilities for use on the research required for their degrees. Some graduate students depend upon working on research projects for the Center as their primary means of support. More are supported from other sources but choose research topics which are within or related to the objectives of the Research Center, obviously because of faculty interests.

Table 1 lists the students enrolled in the department during the grant period according to their relationship to the center.

GRADUATES DURING YEAR

The students who graduated, or completed all work for a degree, during this period (some degrees will be dated January, 1970) are listed below.

TABLE 1 - GRADUATE STUDENTS' RELATIONSHIP TO CENTER

Student	Degree Desired	Worked Part-Time For Center	Traineeship from FWPCA	Other Source of Support
John Carter	M.S.		X	
Kyle Cherry	M.S.		X	
Richard Connor	M.S.			Corps of Eng.
Cecil Cork	M.S.			State of Ala.
Thomas Hardesty	M.S.		X	
Michael Morris	M.S.			FWPCA Research
Harold Sansing	M.S.			State of Tenn.
Alfred Smith	M.S.			FWPCA (on leave)
William Stuart	M.S.			NSF
Gene Dohrman	M.S.		X	
Michael Apple	M.S.		X	
Dean Harshbarger	M.S.			NAPCA
David Kuhlman	M.S.		X	
Joel Fisher	M.S.		X	
William Baumgartner	M.S.			State of Tenn.
Jerry Anderson	Ph.D.			NASA
John Clement Burdick	Ph.D.	X		Corps of Eng.
Julie Hsieh	Ph.D.	X		VU
Louis Motz	Ph.D.	X	X	
Eung Bai Shin	Ph.D.	X		VU
James Speakman	Ph.D.	X	X	
Ning-Hsi Tang	Ph.D.			FWPCA Research
Frederick Ziegler	Ph.D.			NAPCA
Frederick Brunner	Ph.D.			NAPCA
Edward Yandell	Ph.D.			VU
Karl Ayers	Ph.D.			NAPCA
Henry Dalton Tomlinson	Ph.D.			

Also listed is the present status or employment of each graduate, and, in parentheses, the title or subject of his research project.

Anthony S. Johnson, M.S. - Lieutenant, U. S. Air Force (Laboratory Investigation of Phenomena Affecting Reaeration Coefficients).

Louis Motz, M.S. - Graduate student, Vanderbilt University (Reaeration by Wind-Driven Circulation).

Gerald Gross, M.S. - Lieutenant, U. S. Army Corps of Engineers, Da Nang, Viet Nam (Use of Fluorescent Dyes as Tracers in Activated Sludge).

Kyle Cherry, M.S. - Science and math teacher, Celina, Tennessee, High School (temporary) (Effects of Acid Mine Drainage on Dale Hollow Lake and the Obey River).

William Baumgartner, M.S. - Engineer, Tennessee Department of Public Health, Nashville (Extended Aeration Package Plants in Tennessee).

John Koon, M.S. - Ph.D. Candidate, University of California, Berkeley, California (Removal of Color from Vegetable Tanning Liquor).

Harry Walters, M.S. - Engineer, Corps of Engineers, Nashville, Tennessee (Underground Waste Disposal).

Frederick G. Zeigler, Ph.D. - Lieutenant, U. S. Navy Civil Engineering Corps, Da Nang, Viet Nam (Meteorological Effects on Carbon Monoxide Distribution at an Urban Intersection).

Henry Dalton Tomlinson, Ph.D. - Associate Professor, Washington University, St. Louis, Missouri (Color Removal From Vegetable Tanning Solutions).

Ning-Hsi Tang, Ph.D. - Assistant Professor, Washington State University, Pullman, Washington (Moisture Transport in Sludge Dewatering on Sand Beds).

CURRENT RESEARCH PROJECTS

Most of the M.S. candidates who entered the program in September, 1968, are currently (August, 1969) working on their summer research projects and will complete them shortly. Several should complete all the degree requirements by January 1. Several of these research projects are related to the objectives of the Research Center. Below are listed the individual research projects of all students presently doing research. Notice is also given if the project is a Research Center project, and if facilities or supplies purchased with Research Center funds was utilized in the work.

Richard Connor, M.S. Candidate - Discharge of Negatively Buoyant Effluents from Diffusers into Flowing Streams.

Michael Morris, M.S. Candidate - Tracing Polluted Reservoir Inflows with Fluorescent Dyes.

William Stuart, M.S. Candidate - Correlations Among Meteorological Data In Thermal Pollution.

Louis Motz, Ph.D. Candidate - Dispersion of Heated Surface Jets Into Moving Streams (Research Center Project).

James Speakman, Ph.D. Candidate - Effects of Thermal Shock on Fish.

Jerry Anderson, Ph.D. Candidate - Immobilization of Phosphorus in Impoundment Soils.

John Carter, M.S. Candidate - The Diauxie Phenomenon in Activated Sludge.

Michael Apple, M.S. Candidate - Influence of Aeration Geometry on Hydraulic Behavior of Activated Sludge Tanks.

Dean Harshbarger, M.S. Candidate - Effect of Perforated Plates on Pressure Drop and Velocity Distribution in Air Ducts.

Joel Fisher, M.S. Candidate - Dynamics and Kinetics of Phosphate Removal in Activated Sludge Plants.

David Kuhlman, M.S. Candidate - Possible Health Hazards of Water Treatment Chemicals.

John Clement Burdick, Ph.D. Candidate - Using Preimpoundment Soil and Vegetation Data to Predict Reservoir Water Quality (Used Research Center Equipment).

Fred Brunner, Ph.D. Candidate - Dispersion of Carbon Monoxide From a Heavily-Travelled Urban Thoroughfare.

CURRENT EDUCATIONAL PROGRAM

The details of the current graduate educational program are best described by the brochure, "Environmental and Water Resources Engineering - Graduate Study and Research, 1969-1970", copies of which are enclosed with this report. The brochure lists the degree requirements and presents typical programs taken by students in the various areas of concentration. It also contains descriptions of all courses and resumés for all faculty members.

RESEARCH ACCOMPLISHMENTS

TEMPERATURE DISTRIBUTIONS RESULTING FROM COOLING WATER DISCHARGES

Principal Investigators: F. L. Parker, P. A. Krenkel

Research Assistant: E. M. Polk

Project Began: October 1968

Scheduled Completion: October 1970

Critique:

Introduction

The distribution of temperature resulting from the discharge of heated water into a receiving water body is vital to all who make use of our streams, lakes, and coastal waters. The increasing use of our natural watercourses as a source and sink for cooling water has brought about considerable concern regarding the effects of artificial water temperature elevation upon the environment.

Increased temperatures are known to alter the physical, chemical, and biological properties of a water body. Of immediate concern in many areas is the effect of temperature rise upon fish and other life in the aquatic environment. To evaluate this problem, biologists and other interested groups or agencies are seeking straightforward methods

of determining the areas of water body subjected to artificial temperature rises, the magnitude of temperature rises involved, and how the temperature distributions vary with time. Although much of this information may be obtained (at considerable expenditure of time and money) from field measurements at existing sites where heated water is discharged, a means of adequately predicting temperature distributions at proposed plant sites (or for present sites subject to altered conditions in the future) is perhaps of greater need.

Because all biological and chemical activity is temperature dependent to varying degree, thermal discharges into a water body can significantly alter water quality. Of particular concern is the fact that elevated water temperatures cause more rapid biological and chemical oxidation of organic materials while at the same time reducing the level of dissolved gases, particularly oxygen, which the water can hold. Discussion of the many deleterious effects on water quality caused by dissolved oxygen reduction need not be undertaken here.

The effect on the physical properties of waters subjected to thermal inputs may itself create a pollution problem. Industry, although it represents by far the largest contribution of thermal discharges, is subject to detrimental physical effects of thermal pollution. The loss of cooling water can be a serious and costly problem. Ironically, under certain hydraulic and thermal conditions, an industry can disrupt its own cooling water supply by creating a heated overflow. A good understanding of the mechanisms involved in determining temperature distributions is essential to the design and location of both heated effluent discharge structures and cooling water intakes.

It is, therefore, evident that before any thermal discharge can be evaluated in terms of its pollutional effects, the temperature distribution must be known. If the distribution cannot be obtained from field data, it must be predicted by utilizing valid, field tested methods. It is the purpose of this work to develop predictive tools that will be useful in defining the relationship between temperature distributions and thermal pollution.

CLASSIFICATION OF TEMPERATURE DISTRIBUTIONS

The distribution of temperature in a water body receiving a heated effluent is a result of dilution of the heat by mixing and/or heat transfer into or out of the water. While the mixing problem is primarily one of hydrodynamics involving mass transfer, the cooling problem mainly involves heat transfer at the air-water interface. Although the mixing and cooling process may occur simultaneously, it is beneficial to initially separate the two phenomena for purposes of theoretical development.

What happens to a heated water effluent reaching a receiving stream can vary considerably according to the hydraulic and thermal properties of both the discharge and receiving waters. For example, heated discharges into a current may be swept downstream until completely mixed, form a density overflow which extends upstream beyond the plant intake, or form an intermediate density layer in an already stratified reservoir. Such distributions may take on additional complexity as a result of time

variation in discharge temperature and flow, stream flow, and reservoir density structure. For many sites, all of the above mentioned distributions may be evidenced during the course of a year.

Because of the variability in the types of temperature distributions which may be encountered, there seems to be a justifiable need for a criteria which will enable classification of a particular site or set of hydraulic conditions according to the type of temperature distribution that can occur. The information necessary at a particular site to make an initial classification would include:

Receiving Stream:

1. Flow and velocity.
2. Initial temperature distribution.
3. Time variation of the above.
4. Location of cooling water intake.
5. Geometry.

Heated Discharge:

1. Temperature of the heated discharge.
2. Flow and velocity.
3. Time variation of the above.
4. Geometry of the discharge channel.

Meteorological Conditions:

1. Radiation.
2. Air temperature & Humidity.
3. Evaporation.

Utilizing the above parameters it is proposed that criteria be developed which will establish the heat distribution type to be expected at a particular site. Such a classification scheme might appear as

follows:

- I. Steady State Conservative Distribution: No appreciable heat loss.
 - A. Mixing Case: Heat is swept downstream until completely mixed.
 - 1. No geometry effects
 - 2. Considerable geometry effects
 - B. Stratified Case: Heat does not completely mix but forms a density layer.
 - 1. Downstream Distributions Only
 - 2. Upstream and Downstream Distributions
- II. Steady State Non-Conservative Distribution: Significant heat loss or gain.
 - A. Mixing Case
 - B. Stratified Case
- III. Non-Steady State Problem

By establishing categories of particular temperature distribution types, it is felt that theoretical analysis will be simplified, allowing development of useful predictive models. Because of the many parameters involved, a very general classification scheme would necessarily result in a complex and cumbersome model. On the other hand, too specific a classification scheme can lead to the development of distribution models which apply only to relatively few sites.

Of considerable usefulness in distinguishing between the mixing type distribution and the stratified type distribution has been the parameter

grouping called the densimetric Froude number. This criteria may be expressed mathematically as:

$$F = \sqrt{\frac{u^2}{g \frac{\Delta \rho}{\rho_2} H}} \quad (1)$$

where

- F = densimetric Froude number
- u = stream velocity
- g = acceleration due to gravity
- $\Delta \rho = \rho_2 - \rho_1$
- ρ_1 = density of the warm water layer
- ρ_2 = density of the cold water layer
- H = total stream depth.

Theoretically, when the Froude number exceeds 1.0, stratification can no longer exist and heated waters will mix with a colder layer. When Froude numbers are less than 1.0, stratification may exist and heated overflows may form. Critical values of the densimetric Froude number, however, have been reported in the literature from 0.75 to 1.0. Further field investigations will certainly be necessary to more closely establish this value.

MATHEMATICAL MODEL DEVELOPMENT

Analytical descriptions of temperature distributions resulting from condenser water discharge have been proposed and/or developed to deal

with several of the distribution classifications given previously. For the conservative distribution, mixing case, two mathematical models have been developed based on the theory of dispersion of a conservative substance. Both a two dimensional and a three dimensional solution have been derived at Vanderbilt utilizing area-temperature contour relationships which allow broad application in terms of predictive use or use for reduction of field data.

For the non-conservative, two dimensional distribution, a term has been added to the analytical solution to account for heat transfer to the atmosphere. The magnitude of the heat transfer terms may be readily evaluated utilizing a surface heat exchange coefficient.

The three temperature distribution models, their derivation, and discussion of their use is given in an accompanying report (1) entitled "Initial Mixing of Thermal Discharges into a Uniform Current". The derived equations have been developed to predict for a given temperature rise the total surface area and the cross-sectional area at a downstream location occupied by a temperature rise equal to or greater than the given rise. The significant properties of the distributions which arise from the analysis are given from the report as follows.

Properties of Two Dimensional Distributions

1. The surface area varies inversely with the cubic power of the concentration ratio. Other cases (inclusion of surface cooling, three-dimensional distribution) will have a different power law. Applicability of the two-dimensional conservative case

can therefore be judged by comparison of the slopes of the theoretical and data plots.

2. For a given concentration ratio, the area varies with the cubic power of the plant pumping rate. This provides a very simple scaling rule for projecting observations made at one plant size to predictions for an increased plant size. It also indicates that variation in plant pumping rate is an important factor when choosing field test conditions.
3. For a given concentration ratio, the area varies inversely with the square of river flow. The smaller the river flow, the larger the surface area required to achieve the same degree of mixing.
4. The distance from the discharge to the fully mixed contour, L_m , for a discharge into a river flow is:

$$L_m = \frac{wQ_R}{\pi D_y d} \left[1 - \left(\frac{Q_P}{Q_R} \right)^2 \right] \quad (\text{Eq. 81 in Report})^{(2)}$$

where: d = stream depth,

w = stream width,

Q_R = river flow,

Q_P = plant flow,

D_y = lateral diffusion coefficient,

and is a function of the ratio of plant pumping rate to river flow as well as the river flow itself.

4. The one parameter entering the relations which is difficult to evaluate is the lateral dispersion coefficient, D_y . First

testing an observed distribution for fit to the two-dimensional case, then estimating values for D_y will be a necessary objective of field experimentation.

6. Surface cooling can significantly reduce the area over which mixing will take place. In the case of rivers it results in a lower fully mixed temperature rise which can be computed. (Equation 38 in Report)
7. Surface cooling changes the slope of the temperature rise - area relation. (Figure 3 in Report)

Properties of Three-Dimensional Distributions

1. The surface area within a concentration contour varies inversely with the $3/2$ power of the concentration ratio. This is a more rapid decrease than for the two-dimensional non-conservative distribution at the largest estimated die-away. (Figure 4 in Report)
2. The distance from the discharge to the completely mixed contour, L_m , is given by:

$$L_m = \frac{Q_R}{\pi \sqrt{D_y D_z}} \left(1 - \frac{Q_P}{Q_R}\right) \quad (3)$$

(Eq. 82 in Report)

where: D_z = vertical diffusion coefficient.

This distance varies linearly with the ratio of plant pumping rate to river flow as compared to the square of the ratio for the two-dimensional case.

3. The three-dimensional case can be described by the fraction of

cross-sectional area within a concentration contour as a function of distance from the discharge. At a given cross-section location the concentration ratio is a log-linear function of location of cross-sectional area. The inverse slope of the log-linear relation is a simple linear function of distance from the discharge.

WARM-WATER WEDGES

For the conservative, stratified case, theoretical descriptions are being sought to allow prediction of temperature distributions in the vicinity of cooling water discharges. The stratified distribution problem is perhaps the most complex in that advective forces in the receiving water body have less predominance, allowing heated effluents to spread in all directions including upstream against the current. In terms of theoretical description, it is, therefore, useful to separate the upstream temperature distribution problem from the downstream problem.

At present an equation proposed by Bata (2) including a modified version from T.V.A. (3) is being utilized successfully to predict the length of upstream arrested density wedges. This analytical solution has been derived from the hydraulic equations describing flow in a two layered, density stratified fluid system. The length of arrested warm water wedge, as shown in Figure 1, is primarily a function of the densimetric Froude number. The critical value of the densimetric Froude number, as expressed by Bata, is 1.0, with higher values indicating the absence of an upstream distribution. Based on data obtained by Keulegan

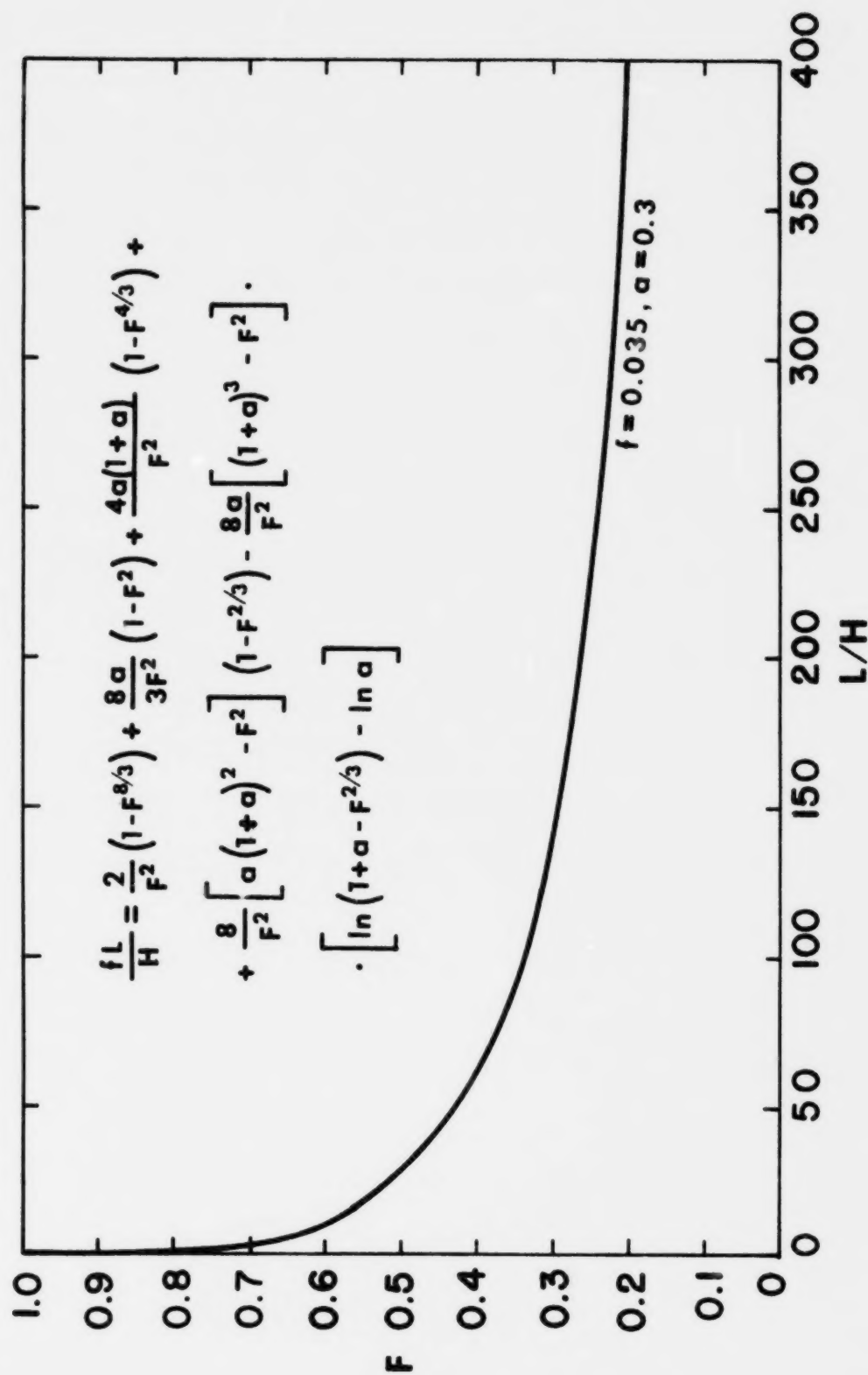


FIGURE 1 - RELATIONSHIP OF DENSIMETRIC FROUDE NUMBER AND LENGTH TO DEPTH RATIO AFTER BATA

for salt wedges (4), T.V.A. has modified the equation to a form dependent upon a critical densimetric Froude number of 0.75. Also, the empirical relationships derived by Chikwendu and Francis (5) in laboratory flumes are being tested against observed temperature data.

FIELD SURVEYS

Since November, 1968, five field surveys have been conducted at four different steam plant sites within the T.V.A. system. The Tennessee Valley Authority cooperated in the surveys by providing relatively steady steam plant loadings and reservoir flows during the twelve hour periods required to gather the data. Both temperature and velocity measurements were made at several stations and numerous cross-sections above and below the point of cooling water discharge in the receiving reservoir. The sites and survey dates are listed below:

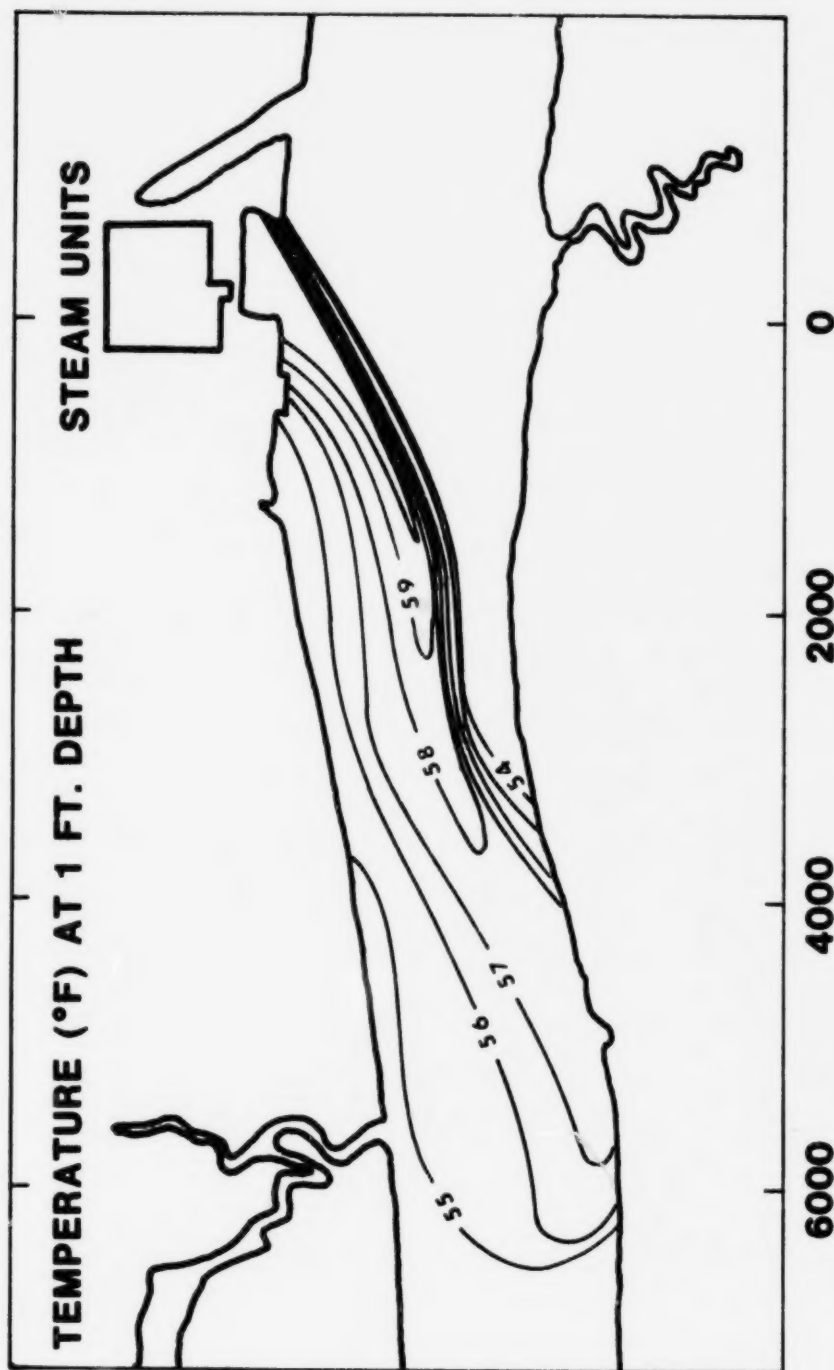
<u>Site</u>	<u>Receiving Stream</u>	<u>Survey Date</u>
Widow's Creek Steam Plant	Guntersville Reservoir	November 20-21, 1968
Gallatin	Old Hickory Reservoir	April 1-3, 1969
Johnsonville	Kentucky Reservoir	May 27-29, 1969
Gallatin	Old Hickory Reservoir	June 21-23, 1969
Bull Run	Melton Hill Reservoir	July 22-24, 1969

The first of the surveys, Widows Creek, was conducted at densimetric Froude numbers greater than 1.0 and thus has been analyzed in terms of the conservative distribution for the mixing case. The data has been

presented in the accompanying report, "Initial Mixing of Thermal Discharges into a Uniform Current". Temperature distributions have been compared in this report to those predicted by the three dimensional distribution model and were found to give reasonably good fits. Other data obtained by T.V.A. at this same site also were shown to compare favorably with the three dimensional model. The data do, however, indicate a higher rate of lateral dispersion and a lesser rate of vertical dispersion than would normally be expected for a conservative substance under similar hydraulic conditions. This discrepancy may well be the result of buoyancy effects of the heated water and shall receive further study. Surface and cross-sectional and temperature contours from which the area data were calculated are shown in Figures 2, 3, and 4.

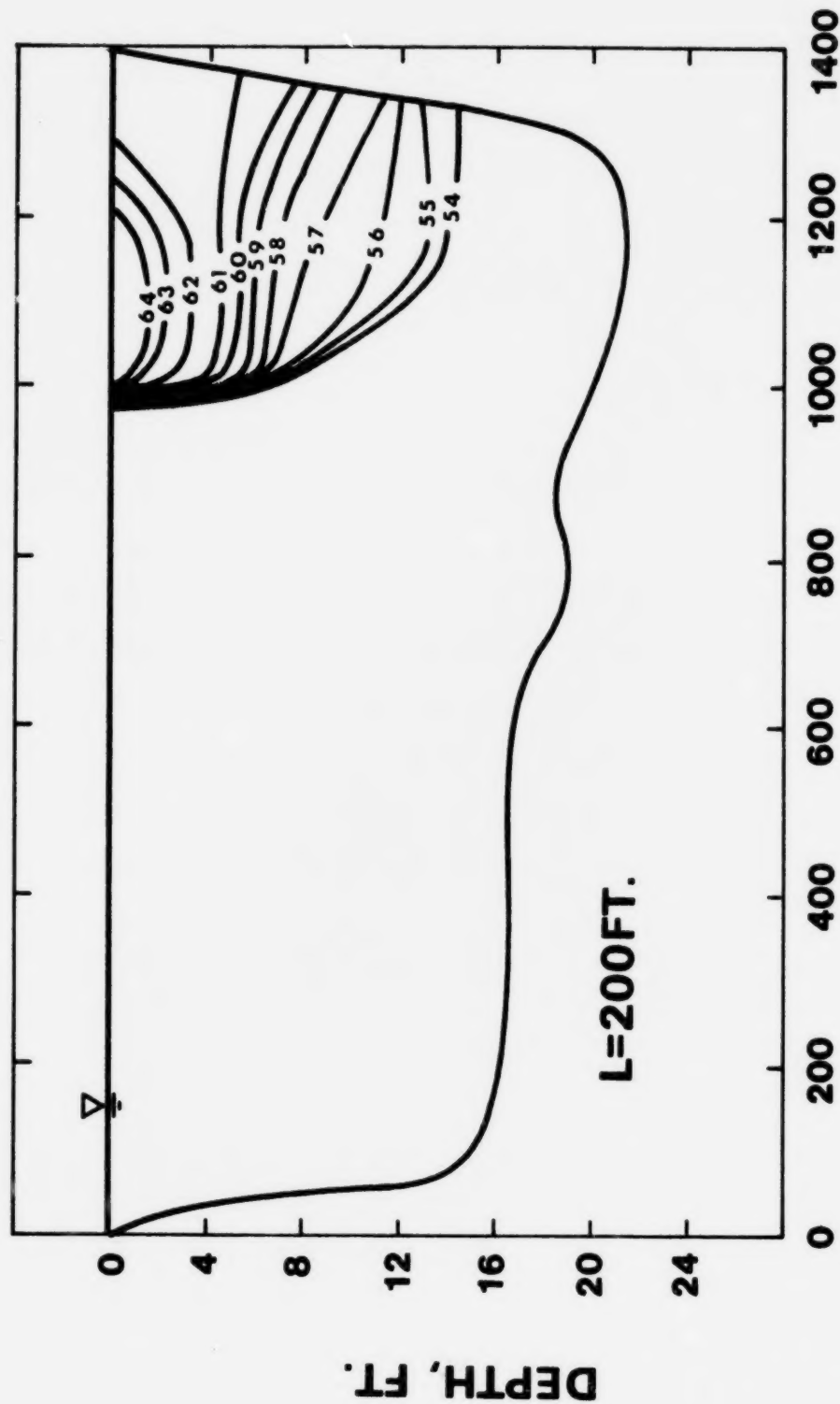
For each of the remaining four sites the data which have been collected indicate a conservative, stratified distribution of temperature. The temperature measurements from three of these surveys show an arrested density overflow upstream of the plant. The lengths of the arrested wedges have been compared to values computed from the equation of Bata and from the T.V.A. modification of the Bata equation. Table 1 gives the results of the comparisons along with other data pertinent to each of the surveys. Figures 5 and 6 show the longitudinal distribution of temperature with depth at two of the sites, and Figure 7 gives a cross-sectional view of temperature contours observed in a heated wedge at the Bull Run site.

The T.V.A. modified form of the Bata wedge solution as indicated in Table 1 gave quite good wedge length predictions for the Gallatin and Johnsonville data. However, it is pointed out that density differences



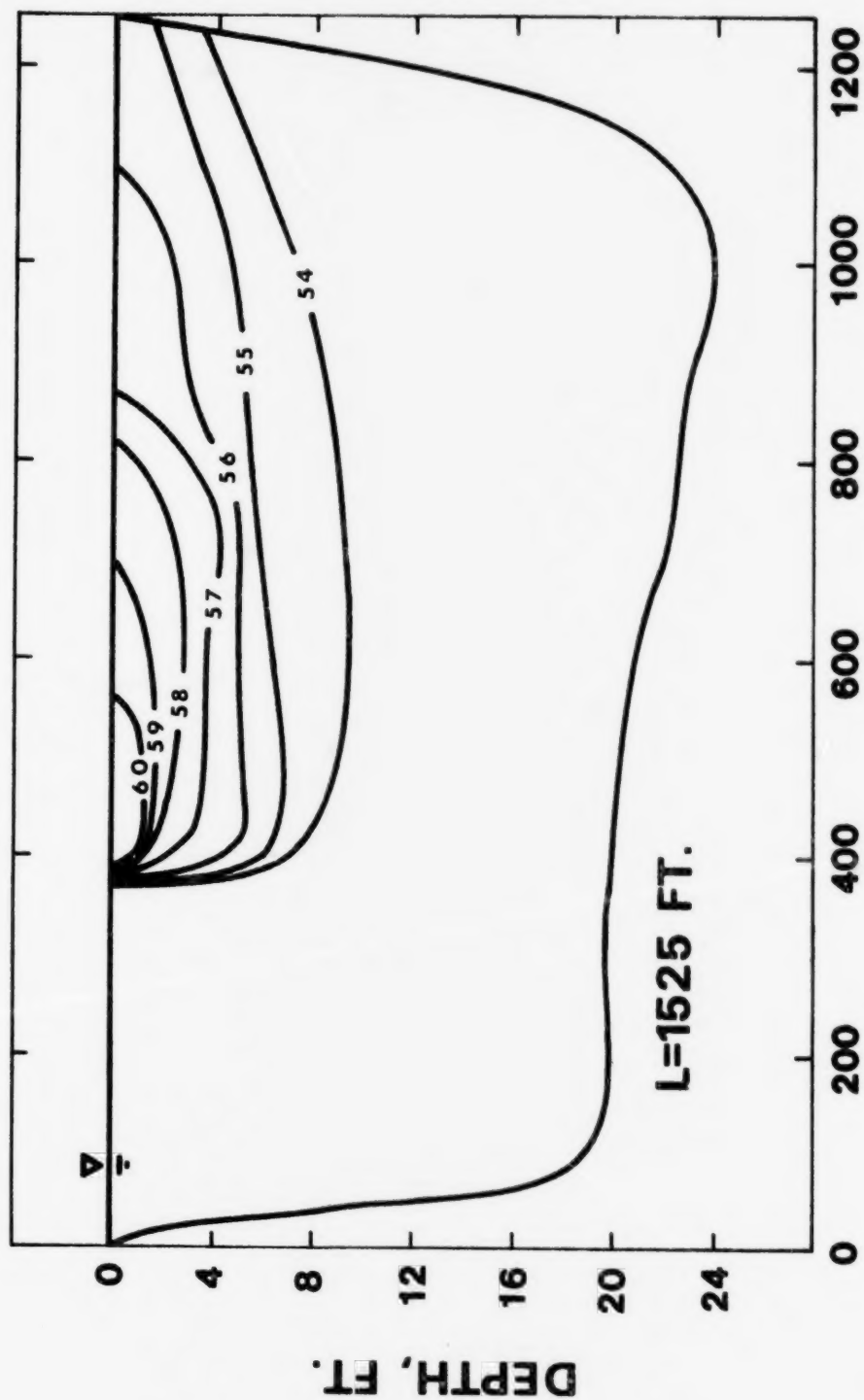
DISTANCE DOWNSTREAM, FT.

FIGURE 2 - SURFACE TEMPERATURES IN THE VICINITY OF WIDOW'S CREEK STEAM PLANT - 11/20/68



DISTANCE FROM LEFT BANK LOOKING DOWNSTREAM, FT.

FIGURE 3 - TEMPERATURES IN THE CROSS-SECTION 200 FEET DOWNSTREAM FROM WIDOW'S CREEK STEAM PLANT - 11/20/68



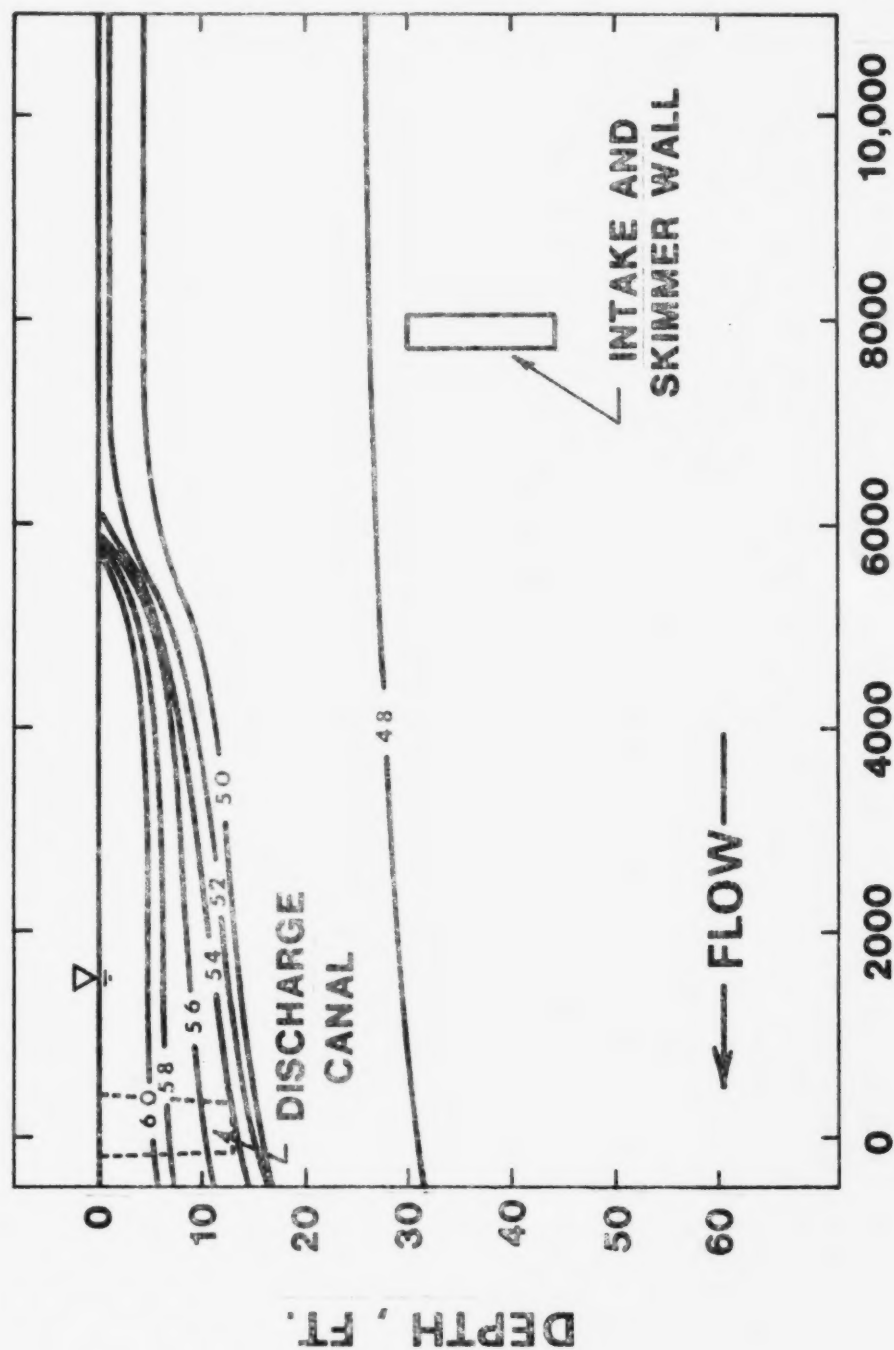
DISTANCE FROM LEFT BANK LOOKING DOWNSTREAM, FT.

FIGURE 4 - TEMPERATURES IN THE CROSS-SECTION 1525 FEET DOWNSTREAM

FROM WIDOW'S CREEK STEAM PLANT - 11/20/68

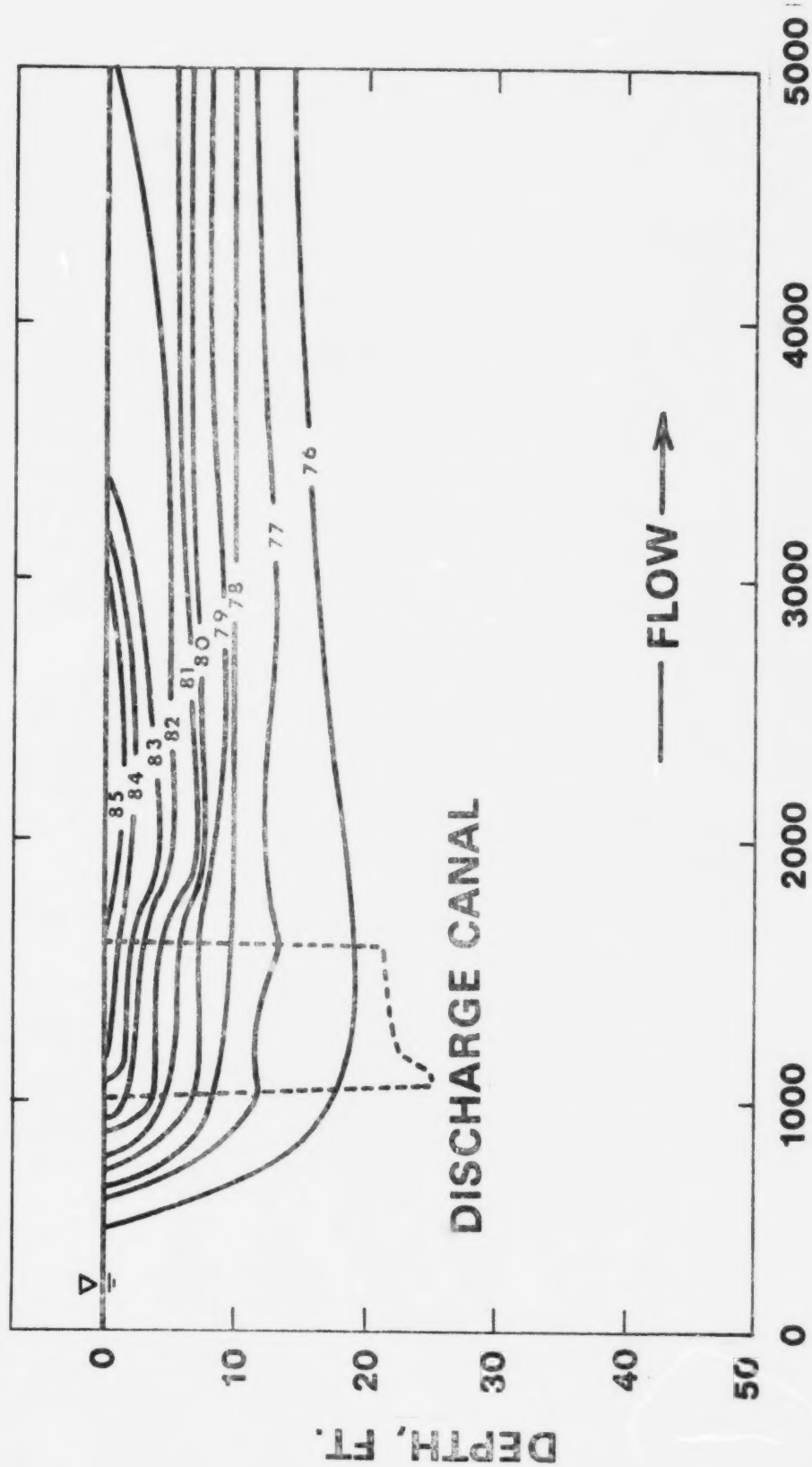
TABLE 1

Parameter	Gallatin 4/3/69	Johnsonville 5/29/69	Gallatin 6/23/69	Bull Run 7/24/69
Capacity, megawatts	1,050	1,200	1,050	900
Load During Survey, megawatts	1,050	1,200	1,050	490-900
Plant Flow, cfs	1,450	2,180	1,450	1,070
Temp. Rise Through Plant, °F	12.4	11	13	10-18.5
Stream Flow, cfs	11,550	26,500	31,100	
Avg. Stream Width, ft.	500	2,000	500	750
Avg. Stream Depth, ft.	75	50	75	25
Avg. Stream Velocity, ft./sec.	0.43	0.58	1.47	.16
Densimetric Froude No.	0.38	0.623	0.970	0.257
<u>Measured Length of Arrested Warm Water Wedge, ft.</u>	6,150	400	No wedge	1,700
<u>Predicted Length of Arrested Warm Water Wedge, ft.</u>				
Bata Equation	6,700	670	< 1	5,750
TVA Modified Bata Equation	6,250	330	No wedge	5,630



DISTANCE ABOVE DISCHARGE, FT.

FIGURE 5 - LONGITUDINAL TEMPERATURE PROFILE UPSTREAM FROM GALLATIN STEAM PLANT



DOWNSTREAM DISTANCE, FT.

FIGURE 6 - LONGITUDINAL TEMPERATURE PROFILE IN THE VICINITY OF JOHNSONVILLE STEAM PLANT - 5/29/69

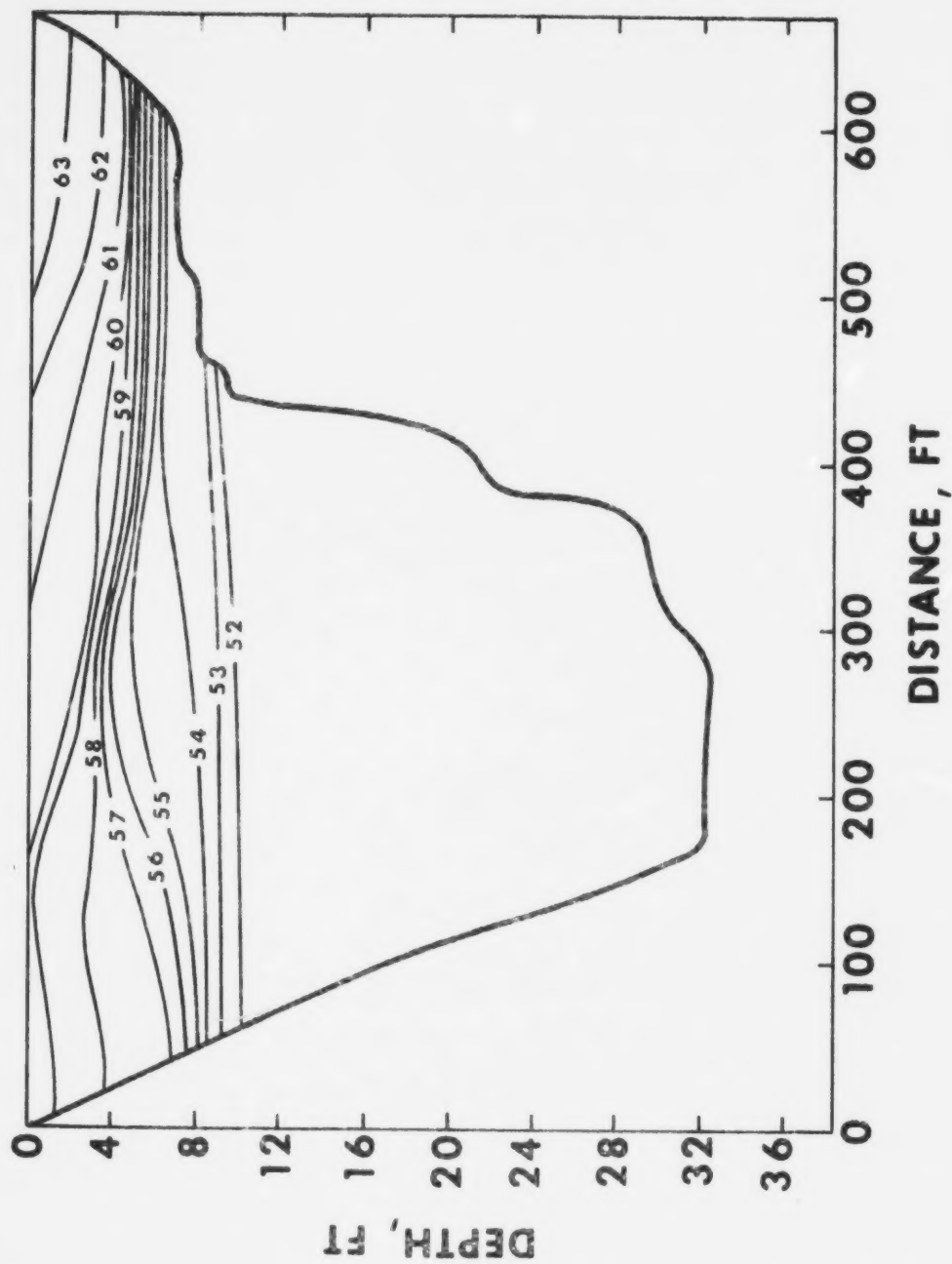


FIGURE 7 - TEMPERATURE PROFILE IN THE CROSS-SECTION UPSTREAM FROM BULL RUN STEAM PLANT - 7/24/69

used to arrive at the densimetric Froude numbers used in the calculations were derived from observed temperatures in the arrested warm water layer, rather than the condenser outlet temperatures. These temperatures, in all cases, were considerably lower than the temperature of the condenser water effluent due to mixing and dilution near the discharge outlet. Thus, before the Bata solution (either modified or unmodified) can be conveniently used for prediction of warm water wedge lengths, a means of estimating the degree of temperature reduction at the outlet must be developed. Investigation of additional steam plant sites and laboratory modeling of heated discharges will be necessary to accomplish this goal.

The obvious disagreement between the predicted and observed wedge lengths at the Bull Run Site is believed to be due to the unsteady flows in the reservoir and variations in plant loading rate. In a 4 hour period during the survey, temperatures in the discharge channel rose from 61°F to 69.5°F and velocities in the receiving stream dropped from 0.35 fps to 0.16 fps.

Data from the Gallatin Survey of June 23, 1969, depict a temperature distribution which forms a stratified density layer downstream with no arrested portion extending upstream. The surface temperature distribution is shown in Figure 8 and a typical cross-section is given in Figure 9. As may be seen from these figures, geometry plays a considerable role in determining the spread of the heated discharge. The data are still being analyzed in terms of both diffusion theory and jet dispersion theory.

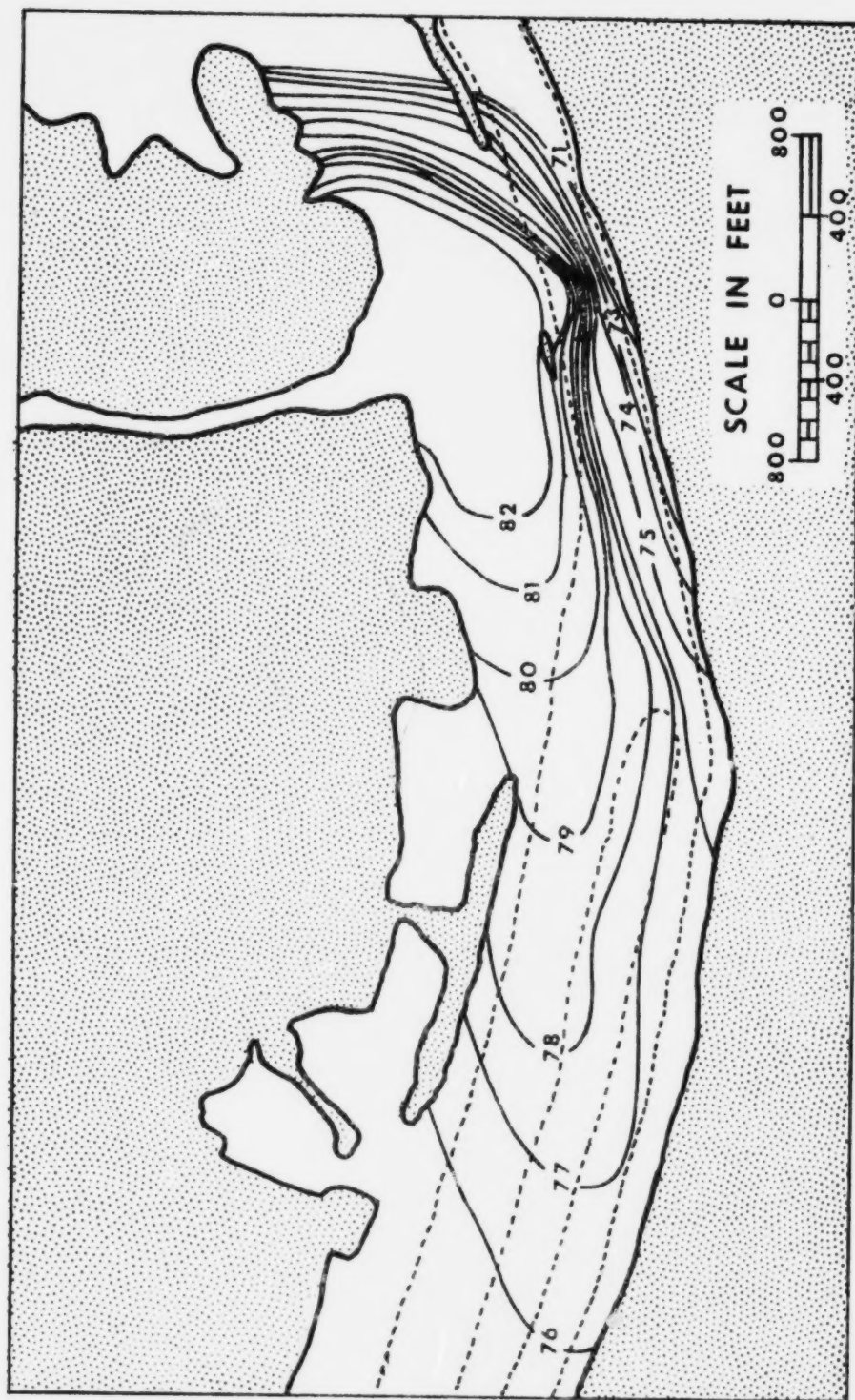


FIGURE 8 - SURFACE TEMPERATURE CONTOURS IN THE VICINITY OF GALLATIN STEAM PLANT - 6/26/69

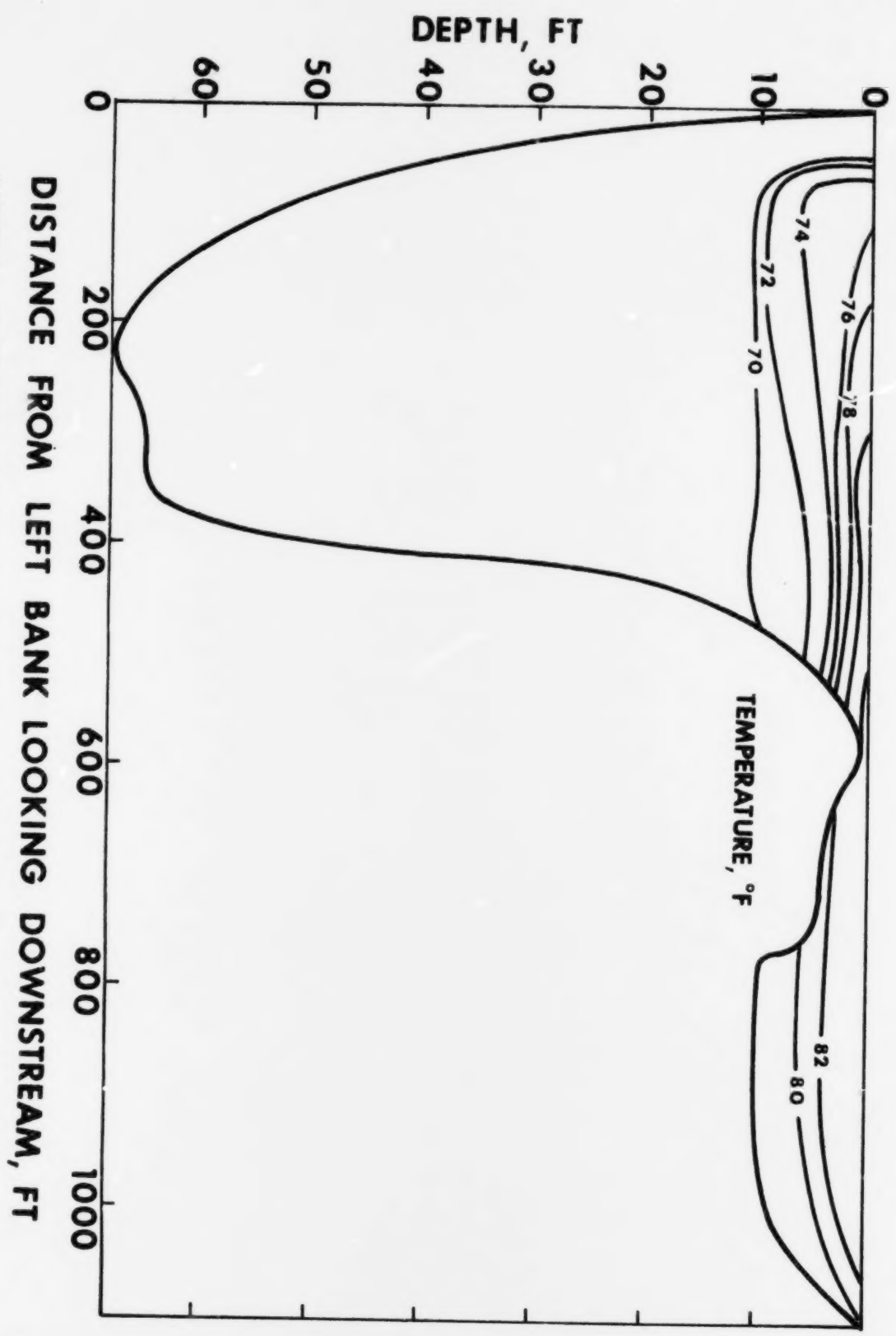


FIGURE 9 - TEMPERATURE CONTOURS IN THE CROSS-SECTION DOWNSTREAM FROM GALATIN STEAM PLANT

CONTINUATION OF MIXING ZONE WORK

Additional temperature distribution data for both the mixing and stratified cases is necessary to adequately test proposed distribution models or develop new ones. At least two of the steam plant sites previously studied, Johnsonville and Eull Run, are known to exhibit temperature distributions in both the mixing and stratified categories depending upon flow levels in the receiving reservoir. A resurvey of these sites will be scheduled when hydraulic conditions indicate a preferred type of temperature distribution. Also, to gather additional data for the conservative, mixing type distribution, two new sites, John Sevier and Petersburg, are proposed for study this year.

To date, no attempt by Vanderbilt has been made to gather data specifically for the purpose of studying the non-conservative (heat loss) type of temperature distribution. The lack of thermo-electric plants in the Vanderbilt area, which create a 10°F or higher mixed temperature rise in the receiving stream, is the primary reason for the avoidance of this type of study. However, with the acquisition of new monitoring equipment to allow rapid measurement of water temperature and meteorological variables, a number of sites in the Southeast are now being considered for study to evaluate heat dissipation by cooling. Letters of inquiry have been sent to a total of thirteen thermal-electric generating plants in the states of Mississippi, Georgia, Alabama, South Carolina, North Carolina, West Virginia, Pennsylvania, and Virginia. Information obtained from the replies to the inquiries will be used to choose sites that should yield useful field data.

NEW EQUIPMENT AND FACILITIES

A number of major equipment purchases have been made during the past six months in order to greatly improve the speed and accuracy of field data acquisition. Boating capabilities have been boosted by the purchase of an additional Mercury outboard motor for our smaller craft and a removable top for protection of instruments used in our larger boat. To enable adequate communication for field personnel during surveys, portable, battery operated walkie-talkies were acquired; and, a Raytheon Portable Survey Fathometer, Recorder, Transducer was obtained to achieve rapid measurement of stream cross-sectional configurations.

Some improvement in temperature measurement capabilities has been obtained through the addition of a Cole-Palmer Digital thermometer and an Electro-Scientific Potentiometric-Voltage Bridge, to be used for calibration of temperature recorders. Adequate field temperature measurement, however, continues to be a major difficulty. To insure the steady state condition of all possible influences during field surveys, measurements must be made as rapidly as possible. The limited time during which condenser flow and temperature, reservoir flow, and meteorological variables can be safely assumed to remain constant is difficult to ascertain in many cases. Steam plant operation is subject to power demands. Hydroelectric dams are subject to peaking power operations. Even if steady inflows and outflows can be maintained in a receiving reservoir for a short time, the internal flow patterns remain subject to transient effects, which may require considerable time to dampen. The constancy of meteorological variables is, of course, subject to

weather conditions.

From a practical standpoint it is, therefore, advisable to obtain field measurements as rapidly as possible and preferably within a few hours. To accomplish this, there is an immediate need for the development of equipment that will rapidly measure and record temperature, velocity, and eventually other parameters, with depth in a reservoir. No commercially available equipment meeting our specifications has been found for use in inland waters. However, a number of companies manufacture comparable equipment for measurements in the ocean. Letters have been sent to more than eighty companies explaining our equipment needs and asking for available information on bathythermographs, pressure and temperature sensors, instrumentation cable and accessories, winches and sounding reels, recorders, and current meters. The large volume of information received in reply is currently being evaluated in an effort to arrive at an economical system to serve our needs.

Instrumentation for the measurement of meteorological variables has been implemented during the past six months by the purchase of an Epply-180 Degree Solar Pyranometer for the measurement of total sun and sky radiation. An Instrument Corporation of America Model 400 Portable Potentiometric Recorder was purchased for use with the Epply under field conditions where no power is available. Also, our Gill Bivane Anemometer has been adopted for remote field use by the purchase of two Esterline Angus Portable Battery operating Servo-Recorders. A standard weather bureau instrument shelter has been obtained to house the instruments in the field.

A substantial improvement in field survey mobility should be

attained with the arrival of a Ford Econoline Van which has been leased. This heavy duty panel truck will be primarily used to transport instruments and our large boat to and from survey sites. A special generator will be installed in the truck to supply 110 volt A.C. power for instrument use at remote locations.

REFERENCES

1. Edinger, John E., and Polk, Edward M., Jr., "Initial Mixing of Thermal Discharges into a Uniform Current", Tech. Report No. 1, Center for Research and Training in the Hydrologic and Hydraulic Aspects of Water Pollution Control, Vanderbilt University, Nashville, Tennessee, October, 1969.
2. Bata, Geza L., "Recirculation of Cooling Water in Rivers and Canals", Journal of the Hydraulics Division, Am. Soc. of Civil Engr., HY 3, June, 1957.
3. Tennessee Valley Authority, "Browns Ferry Nuclear Plant Preliminary Intake - Outlet Design Studies", Laboratory Report No. 1, Division of Water Control Planning, Norris, Tennessee, November, 1966.
4. Keulegan, Garbis H., "Interfacial Instability and Mixing in Stratified Flows", Journal of Research of the National Bureau of Standards, U.S. Department of Commerce, Vol. 43, November, 1949.
5. Chikwendu, L. N., and Francis, J. R. D., "Arrested Water Layers in Curved Rivers", Journal of Institution of Water Engineers, 21, 3, 351-366, May, 1967.

HEATED SURFACE JETS DISCHARGED INTO A FLOWING AMBIENT STREAM

Principal Investigator: Barry A. Benedict
Research Assistant: Louis H. Motz
Project Begun: October 1968
Scheduled Completion: July 1970

Critique:

Introduction

When waste heat from steam-electric power plants is discharged into a receiving water body, the spatial distribution of the heat in the water body is a function of the hydrodynamic variables of the discharge and the receiving water body. When the velocity field of the ambient water body is influenced by the cooling water discharge velocity, and the heat initially advected almost perpendicular to the river flow, then the spatial distribution of temperature can be described in terms of a surface jet discharging at some initial angle to the ambient flow and being deflected downstream by the momentum of the ambient velocity. The decrease in temperature rise along the jet axis is due to the entrainment of colder ambient water into the jet as the jet spreads laterally and, to some extent, vertically. Meteorological variables are considered unimportant in describing the mixing of the heated water because of the relatively small size of the jet surface area. Several

thousand feet downstream from the discharge, after mixing takes place, surface exchange of heat does become important, but that is not considered here.

Shape of the Surface Jet

Observations of warm water surface jets indicate that a surface jet may either be two or three dimensional. For a jet to be two-dimensional, the change in depth along the axis should be zero. For a jet to be three-dimensional, the depth should increase along the axis just as the width increases. Primarily, two forces determine the extent of vertical spreading. The inertial force, or the difference between the axial velocity of the jet and the ambient velocity, creates the shearing force which entrains ambient fluid, causing the jet boundary to spread laterally and vertically. The buoyancy force due to the density difference between the heated surface jet and the heavier ambient fluid opposes the vertical spreading of the jet. When the inertial forces dominate, the jet will spread equally in the vertical and lateral directions. However, when the buoyancy force is large, vertical spreading is suppressed.

Quantitatively, vertical spreading, or vertical entrainment, is an inverse function of the Richardson Number of the jet,

$$Ri = \frac{\Delta \rho g z}{\rho (U - U_a)^2} \quad (1)$$

where ρ = density of the jet

$\Delta \rho$ = density difference between the jet and the ambient flow

g = acceleration of gravity

z = the depth of the jet

U = axial velocity of the jet

U_a = ambient velocity.

When the buoyancy force is large, or the Richardson Number greater than 1, vertical entrainment is small. When the inertial force is large, or the Richardson Number less than 1, vertical entrainment takes place.

In many field cases, the density difference due to heated discharges is large, and the square of the velocity difference is small, particularly when the initial jet velocity is not much greater than the ambient velocity. Thus, the initial Richardson Number of the jet is 1, or very close to 1. Field observations by Zeller (1967) and experiments by Ellison and Turner (1959), and Jen, Wiegel, and Mobarek (1964), indicate that the Richardson Number along the jet axis changes rapidly from an initial value less than 1 to a value equal to or greater than 1, and that vertical entrainment decreases to almost zero along the axis. Thus, if the initial Richardson Number of the jet is 1, or close to 1, the decrease in temperature rise along the jet axis can be approximately described in terms of a two-dimensional surface jet deflected downstream by the ambient velocity.

FORMULATION OF THE PROBLEM

Conservation Equations

The differential equations for conservation of mass flux, momentum flux, and energy flux can be integrated over the cross-sectional area

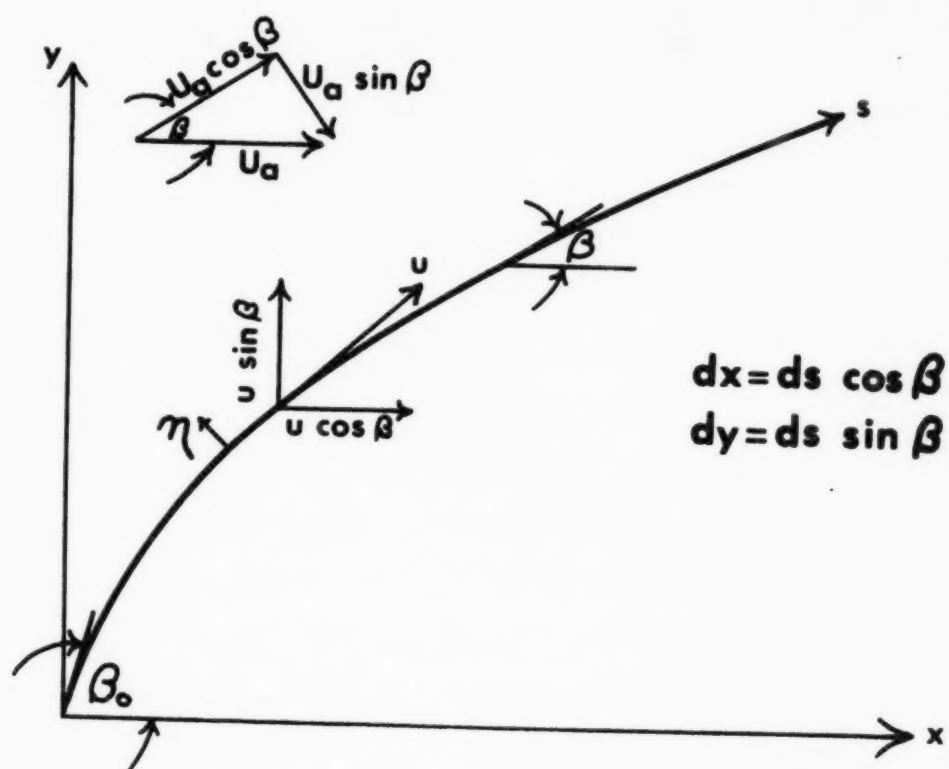


FIGURE 1 - DEFINITION SKETCH

of a two-dimensional momentum jet to obtain integral equations based on the method of Morton, Taylor and Turner (1956). A definition sketch is shown in Figure 1.

Conservation of Volume Flux - Integrating the volume continuity equation over the cross-section gives the relation between the rate of change of volume flux along the jet axis and the flow into the jet across the outer edge,

$$\frac{d}{ds} \int_A u \, dA = \int_C v_i \, dC \quad (2)$$

where u is the jet velocity directed along the s axis, v_i is the inflow velocity, dA is the differential area, and C is the circumference through which entrainment takes place. This inflow, or entrainment, velocity according to Morton (1961) is proportional to the magnitude of the difference between a characteristic velocity along the jet and the parallel velocity of the ambient fluid.

If this entrainment is expressed as an equality, then

$$v_i = E(U - U_a \cos \beta) \quad (3)$$

where U is the centerline velocity, $U_a \cos \beta$ is the parallel component of the ambient velocity U_a , β is the angle between the jet and the ambient current, and E is defined as the entrainment coefficient.

Substituting this expression for entrainment, Equation 3, into the continuity relationship, Equation 2, gives the integral form of the volume continuity equation,

$$\frac{d}{ds} \int_A u \, dA = C E (U - U_a \cos \beta) \quad (4)$$

Conservation of Momentum - The momentum equation along the jet axis can be integrated over the cross-section to give the relation between the rate of change of jet momentum flux and the rate of entrainment of ambient momentum flux. For convenience the resulting equation can be resolved into its longitudinal and lateral components along the x and y axes, respectively. In the x-direction, the rate of change of momentum flux is equal to the rate of entrainment of ambient momentum flux, or

$$\frac{d}{ds} (\int u^2 dA \cos \beta) = C E (U - U_a \cos \beta) U_a \quad (5)$$

In the y-direction, the rate of change of momentum flux is zero, since all the ambient flow is oriented along the x-axis, or

$$\frac{d}{ds} (\int u^2 dA \sin \beta) = 0 \quad (6)$$

Conservation of Temperature - If temperature can be treated as a conservative property, which is reasonable considering the size of the jet surface area, the integrated temperature equation can be written

$$\frac{d}{ds} (\int u T' \, dA) = 0 \quad (7)$$

where T' is the temperature rise at any point in the cross-section, and is measured from the upstream temperature.

Equations 4, 5, 6 and 7 represent the general integrated forms of the

equations of volume, momentum, and heat flux.

Velocity and Temperature Profiles

Continuity Equation - If the velocity distribution of the jet is approximated by a Gaussian profile, then the velocity u at any point in the cross-section can be related to the centerline velocity U by

$$u = U \exp(-\eta^2/2\sigma^2) \quad (8)$$

where σ = standard deviation and η = axis perpendicular to the s axis.

Substituting Equation 8 into the integral on the left side of the continuity equation, Equation 4, gives

$$\int_{-b}^{+b} U \exp(-\eta^2/2\sigma^2) z d\eta = Uz \int_{-\infty}^{+\infty} \exp(-\eta^2/2\sigma^2) d\eta \quad (9)$$

where b is the jet half-width and $dA = z d\eta$, where z = jet depth. The integral on the right side of Equation 9 is a definite integral whose value is $\sqrt{2\pi} \sigma$. Equating this result to the right side of the continuity equation, Equation 4, gives, for the continuity equation,

$$\frac{d}{ds} (Uz\sqrt{2\pi} \sigma) = 2z E(U - U_a \cos \beta) \quad (10)$$

If the half-width b is defined as

$$b = \sqrt{2} \sigma \quad (11)$$

where $2z = C$, and this relation, Equation 11, substituted in Equation 10, then the continuity equation can be written in terms of the centerline

velocity and jet width as

$$\frac{d}{ds} (Ub) = \frac{2E}{\sqrt{\pi}} (U - U_a \cos \beta) \quad (12)$$

Momentum Equations - The square of the velocity U is approximated using Equation 8,

$$u^2 = U^2 \exp(-\eta^2/\sigma^2) \quad (13)$$

Upon substituting this relation into the general form of the x-momentum equation, Equation 5, and using the relations $dA = z d\eta$ and $C = 2z$, and the definition of the half-width, Equation 11, then the x-momentum equation can be written in terms of the centerline velocity and jet width as

$$\frac{d}{ds} (U^2 b \cos \beta) = \sqrt{2} \frac{2E}{\sqrt{\pi}} (U - U_a \cos \beta) U_a \quad (14)$$

Similarly, the y-momentum equation, Equation 6, can be written in terms of U and b as

$$\frac{d}{ds} (U^2 b \sin \beta) = 0 \quad (15)$$

Temperature Equation - If the temperature rise distribution is approximated by a Gaussian profile, then the temperature rise T' in the cross-section is related to the centerline temperature rise T by

$$T' = T \exp(-\eta^2/2\sigma^2) \quad (16)$$

Substituting Equation 16 into the general form of the temperature equation, Equation 7, gives the conservation of temperature equation in terms of U, T and b, or

$$\frac{d}{ds} (UTb) = 0 \quad (17)$$

Summary

The integrated mass, momentum, and temperature rise equations give a system of 4 equations and 4 unknowns:

Four Equations:

continuity:

$$\frac{d}{ds} (Ub) = \frac{2E}{\sqrt{\pi}} (U - U_a \cos \beta) \quad (12)$$

x-component momentum:

$$\frac{d}{ds} (U^2 b \cos \beta) = \sqrt{2} \frac{2E}{\sqrt{\pi}} (U - U_a \cos \beta) U_a \quad (14)$$

y-component momentum:

$$\frac{d}{ds} (U^2 b \sin \beta) = 0 \quad (15)$$

temperature rise:

$$\frac{d}{ds} (UTb) = 0 \quad (17)$$

Four Unknowns:

U, T, b, β

The geometry of the jet as shown in Figure 1 gives two additional equations and unknowns, or

Two Geometry Equations:

$$\frac{dx}{ds} = \cos \beta \quad (18)$$

$$\frac{dy}{ds} = \sin \beta \quad (19)$$

Two Unknowns:

x, y

Thus, there are six unknowns - U, T, b, β , x and y - and six equations, all functions of the jet axis distance s.

Solution of the Equations

Temperature Equation - The temperature rise T is in only one of the above equations, Equation 17. This equation can be integrated immediately to give

$$\frac{U T b}{U_o T_o b_o} = 1 \quad (20)$$

where U_o , T_o , and b_o are the initial values of velocity, temperature rise, and jet half-width, respectively.

Thus, the temperature rise ratio T/T_o along the jet axis s can be determined by solving the remaining equations for values of the velocity ratio U/U_o , and the width ratio b/b_o .

Dimensionless Volume and Momentum Flux - The two dynamic equations

and the volume continuity equation are made non-dimensional for generality.

Defining V as the dimensionless volume flux and M as the dimensionless momentum flux,

$$V = \frac{U b}{U_o b_o}, M = \frac{U^2 b}{U_o^2 b_o} \quad (21)$$

Equations 12, 14 and 15 take the respective forms,

$$\frac{dV}{dS} = \frac{M}{V} - A \cos \beta \quad (22)$$

x-component momentum flux:

$$\frac{d(M \cos \beta)}{dS} = \sqrt{2} A \left(\frac{M}{V} - A \cos \beta \right) \quad (23)$$

y-component momentum flux:

$$\frac{d(M \sin \beta)}{dS} = 0 \quad (24)$$

where S is the dimensionless jet axis distance,

$$S = (2E/\sqrt{\pi} b_o) s \quad (25)$$

and A is the ratio of the ambient velocity to the initial jet velocity,

$$A = U_a/U_o \quad (26)$$

Particular Solutions - The solutions to Equations 22, 23, and 24 are conveniently expressed in terms of the momentum flux M . The solution for the volume flux is found to be

$$V = \frac{(M^2 - I^2)^{\frac{1}{2}} - (1 - I^2)^{\frac{1}{2}} + \sqrt{2} A}{\sqrt{2} A} \quad (27)$$

The solution for the angle β is

$$\beta = \sin^{-1}(I/M) \quad (28)$$

where $I = \sin \beta_0$.

The differential equation for the dimensionless jet axis distance S ,

$$\frac{dS}{dM} = \frac{M}{(M^2 - I^2)^{\frac{1}{2}}} \frac{1}{\sqrt{2}A} \left(\frac{V}{M - AV \cos \beta} \right) \quad (29)$$

can be integrated numerically from $S = 0$ with $M_0 = 1$, $V_0 = 1$, and $I = \sin \beta_0$ to give the relation between the momentum flux M and the jet axis S .

After solving Equation 29 for S and M , then the dimensionless volume flux V , momentum flux M , and the angle β can be expressed as functions of S , the dimensionless jet axis distance.

By employing the definitions of the volume and momentum flux, Equation 21, the ratio of the jet velocity U along S to the initial jet velocity is found to be

$$U/U_0 = M/V \quad (30)$$

The ratio of the temperature rise T to the initial temperature rise T_0 along the axis S is found from Equations 20 and 21 to

$$T/T_0 = 1/V \quad (31)$$

The ratio of the jet half-width b along the axis S to the initial half-width b_0 is found from Equation 21 to be

$$b/b_0 = v^2/M \quad (32)$$

The geometry equations, Equations 18 and 19, when made non-dimensional, can be written

$$\frac{dX}{dS} = \cos \beta \quad (33)$$

$$\frac{dY}{dS} = \sin \beta \quad (34)$$

where

$$X = (2E/\sqrt{\pi}b_0)x, \quad Y = (2E/\sqrt{\pi}b_0)y \quad (35)$$

In summary, the ratios of velocity, temperature, and jet half-width - U/U_0 , T/T_0 , b/b_0 - and the angle β can be solved in terms of the jet axis S . Then, the rectangular coordinates X and Y can be located by integrating Equations 33 and 34 along the axis S ,

$$X = \int_0^S \cos \beta dS \quad (36)$$

$$Y = \int_0^S \sin \beta dS \quad (37)$$

COMPARISON OF PROPOSED MODEL TO FIELD DATA

Zone of Flow Establishment

In practical applications, the zone of flow establishment can be defined using the method of Fan (1967). A definition sketch and the jet trajectories obtained by G6rdier (1959), Jordinson (1956), and Keffer and Baines (1963) near the nozzle are shown in Figure 2.

Based upon G6rdier's results, the length of the zone of establishment is assumed by Fan to follow the relation expressed in Figure 3.

Fan measures the initial angle from the trajectories shown in Figure 2 and relates the angle to the velocity ratio U_a/U_o as shown in Figure 4. The relation between the initial angle β_o at the end of the zone of flow establishment and the ratio U_a/U_o is expressed as

$$\beta_o = 90^\circ - 110^\circ A \quad (38)$$

These relations, valid only for discharges perpendicular to the ambient velocity, are obtained from experiments on axi-symmetric jets but are assumed to be applicable to two-dimensional surface jets as well.

By considering the conservation of heat between the two cross-sections $0'$ and 0 ,

$$U_o T_o D = UT \frac{\sqrt{\pi}}{\sqrt{2}} b_o \quad (39)$$

the jet half-width at 0 is found to be

$$b_o = 0.80 D \quad (40)$$

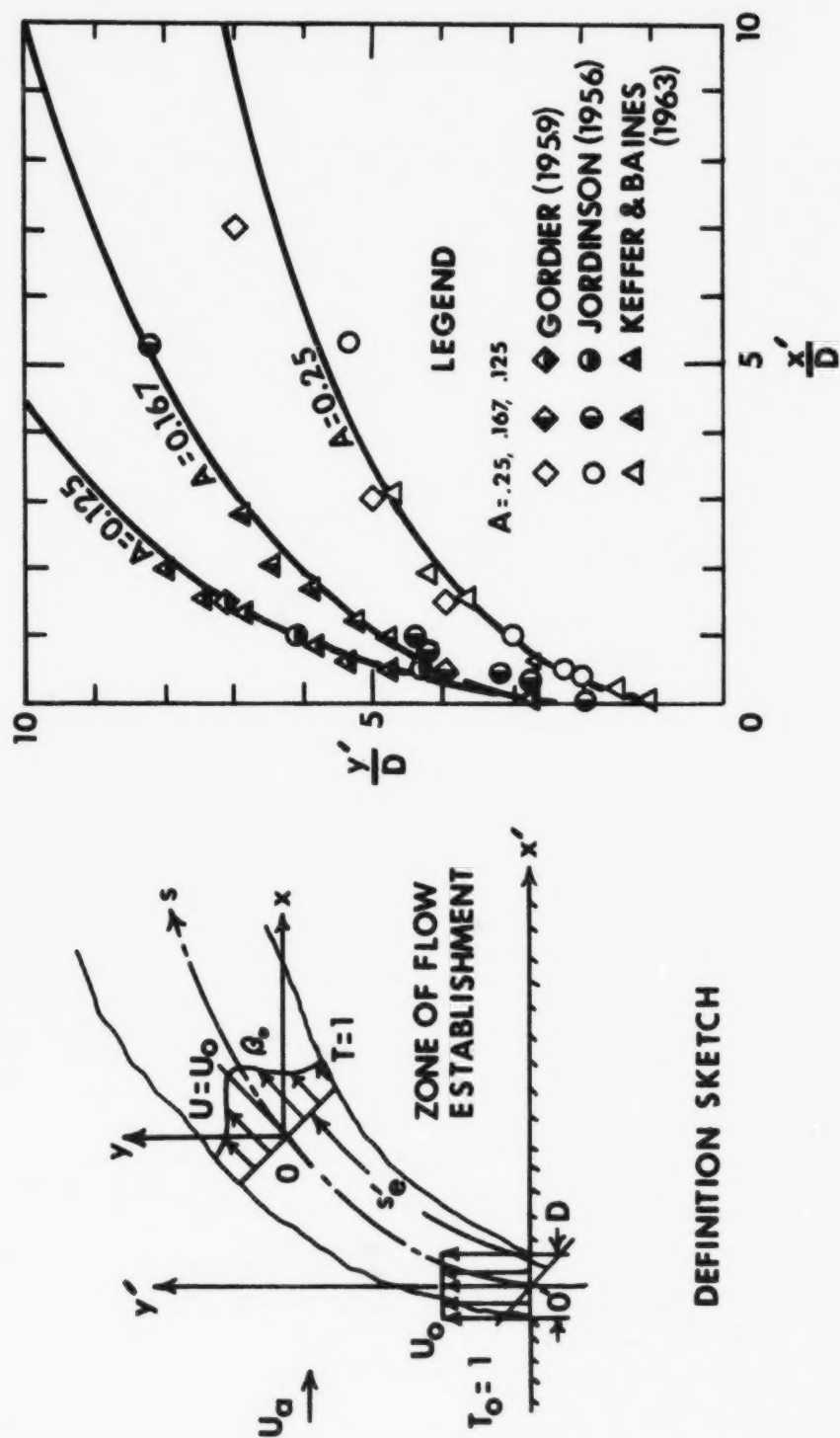


FIGURE 2 - DEFINITION SKETCH AND MEASURED TRAJECTORIES FOR THE ZONE OF FLOW ESTABLISHMENT

($0' \rightarrow 0$) OF ROUND JETS IN CROSS-STREAMS AT $A = .25, .167, \text{ and } .125$ (AFTER FAN (1967)).

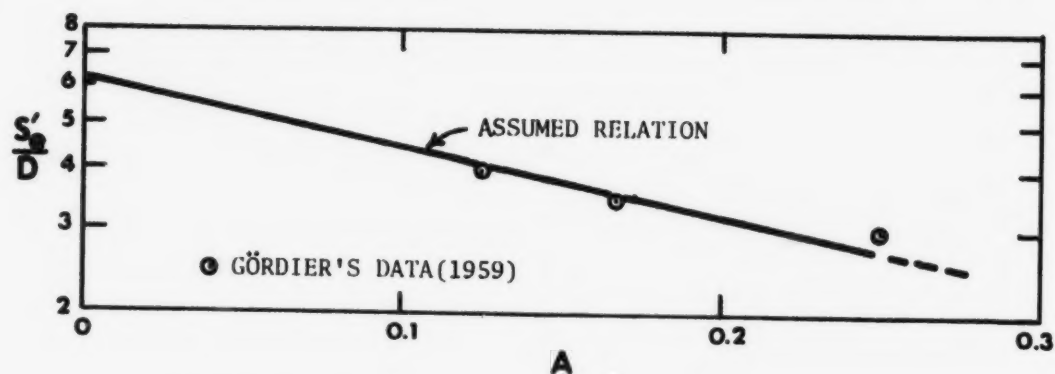


FIGURE 3 - VALUES OF s'_e/D , LENGTH OF THE ZONE OF FLOW ESTABLISHMENT, AS A FUNCTION OF A FOR JETS IN UNIFORM CROSS-STREAMS (AFTER FAN (1967)).

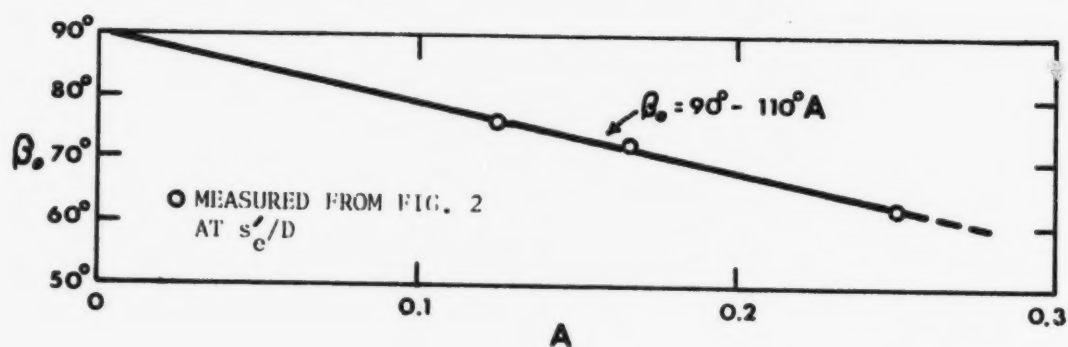


FIGURE 4 - INITIAL ANGLE β_0 AS A FUNCTION OF A FOR JETS IN UNIFORM CROSS-STREAMS (AFTER FAN (1967)).

since the temperature rise T_0 and the jet velocity U_0 at $0'$ are equal to the centerline values T and U at 0 .

Data Collection

In order to test the proposed model, data collected at T.V.A.'s Widows Creek Steam Plant were used. The data were collected over a period of time during which plant discharge and river flow rate were maintained very near steady state conditions. The cooling water from the condensers is discharged into a small coal-barge harbor and flows directly onto the river surface with a minimum of mixing and dissipation. Velocity measurements taken at several stations in the river indicated that the velocity field of the receiving, ambient water body was influenced by the discharge. Since the discharged heat is initially advected across the river almost perpendicular to the river flow, its spatial distribution can be described in terms of a jet discharging at some initial angle to the ambient flow. Temperature profile measurements indicate that the jet spreads laterally approximately 10 times greater than it spreads vertically due to the buoyancy of the heated jet. Thus, the application of the two-dimensional surface jet theory is considered reasonable.

Parameter Evaluation

Velocity Ratio - The river flow rate Q_r is 26,174 cfs. Velocity measurements from a control section upstream from the discharge indicate an ambient (river) velocity of 1 fps. The plant discharge Q_p is equal to 2370 cfs. The initial jet velocity is on the order of 4 fps. Thus,

the ratio of ambient velocity to initial jet velocity is $A = 0.25$.

Initial Width - Observations of the jet indicate a jet depth of approximately 10 feet. From $Q = VA$, the initial width D is on the order of 60 ft. From Equation 40, the initial jet half-width $b_o = 48$ ft.

Zone of Flow Establishment - From Equation 38, the initial angle at the end of the zone of flow establishment is $\beta_o = 60^\circ$. From Figure 3, the length of the zone of establishment is $s'_e/D = 2.8$, or $s'_e = 170$ ft. Fitting the observed temperature to the predicted temperature, as shown in Figure 5, gives a value for the entrainment coefficient $E = 0.09$. The non-dimensional length of the zone of flow establishment S_e is found from $S_e = (2E/\sqrt{\pi} b_o)s'_e$ to be $S_e = 0.4$. Thus, $S = 0.4$ is the initial value from which Equation 29, the differential equation relating S to M , is integrated, rather than $S = 0$.

Predicted and Observed Values - Values of T/T_o and b/b_o as functions of S are predicted by integrating Equation 29 numerically and then using Equations 31 and 32. Next, Equations 36 and 37 are integrated numerically to locate the predicted jet axis S in terms of X and Y . Table 1 shows the parameters used in reducing the observed data. Figures 5 and 6 show the predicted and observed values of T/T_o vs. S and b/b_o vs. S , respectively. Figure 7 shows the predicted jet axis and the observed temperature contours, in terms of x/b_o , y/b_o and s/b_o , from Equations 35 and 25.

Table 1
WIDOWS CREEK DATA

Station	Distance along axis, s, ft.	s/b_o $b_o = 48$ ft.	$S = (2E/\sqrt{\pi}b_o)s$ $E = 0.09$	Temperature $^{\circ}\text{F}$	Temp. Rise from 53.2°F	T/T_o	b	b/b_o
R-1	670	14	1.4	64.9	11.7	.82	300	6.26
R-2	2,105	44	4.4	60.2	7.0	.49	420	8.75
R-3	3,940	82	8.2	58.6	5.4	.38	480	10.00
R-4	5,460	114	11.4	57.9	4.7	.33	600	12.5
R-5	7,200	148	14.8	57.6	4.4	.31		
R-6	8,540	178	17.8	54.6	1.4	.098		
R-7	10,100	210	21.0	55.0	1.8	.127		

$$A = U_a/U_o = 0.25$$

$$T_o = 14.2^{\circ}\text{F}$$

$$Q_r = 26,174 \text{ cfs.}$$

$$Q_p = 2,370 \text{ cfs.}$$

$$b_o = 48 \text{ ft.}$$

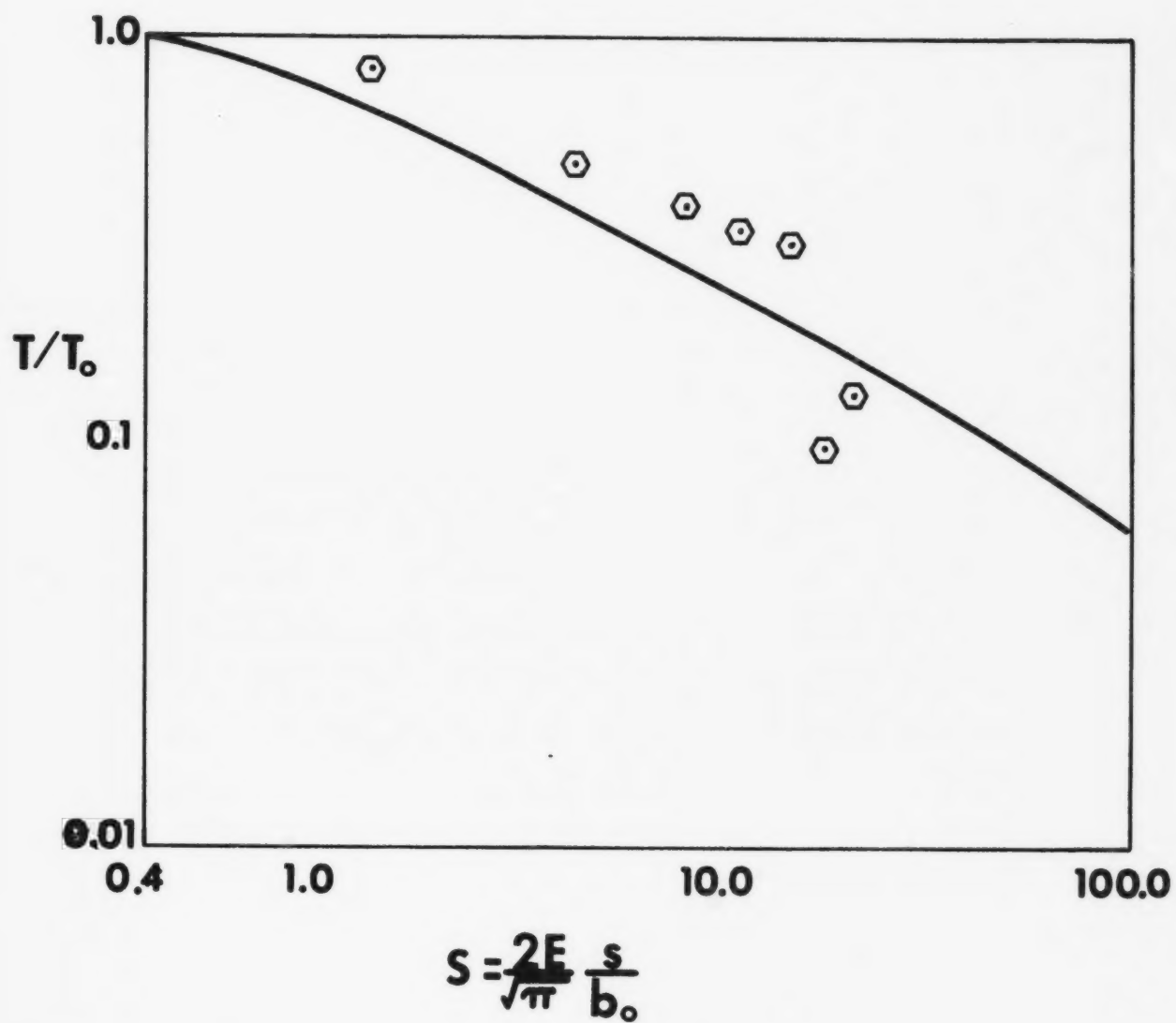
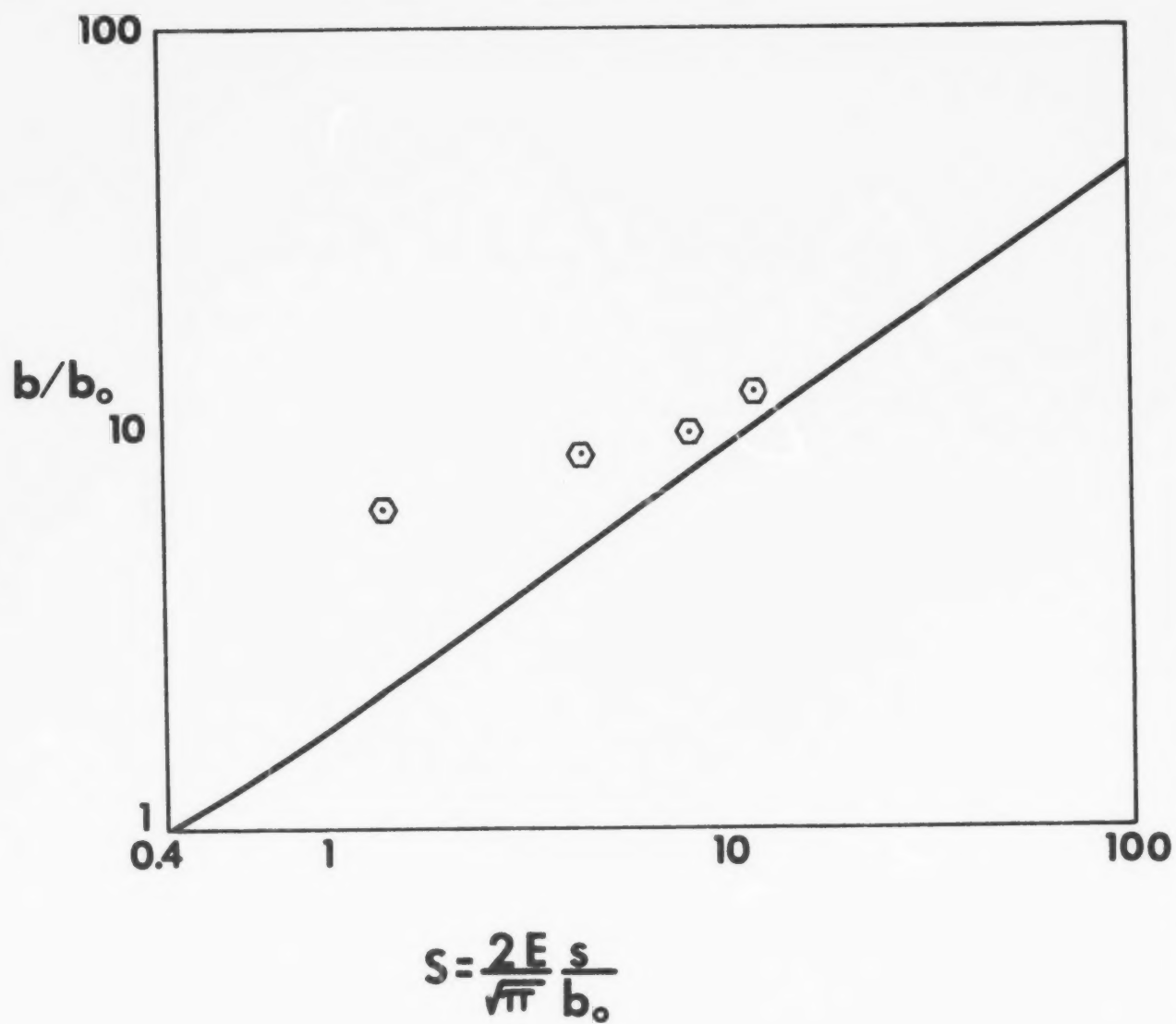


FIGURE 5 - PREDICTED AND OBSERVED T/T_0 VS. S

FIGURE 6 - PREDICTED AND OBSERVED b/b_0 VS. S

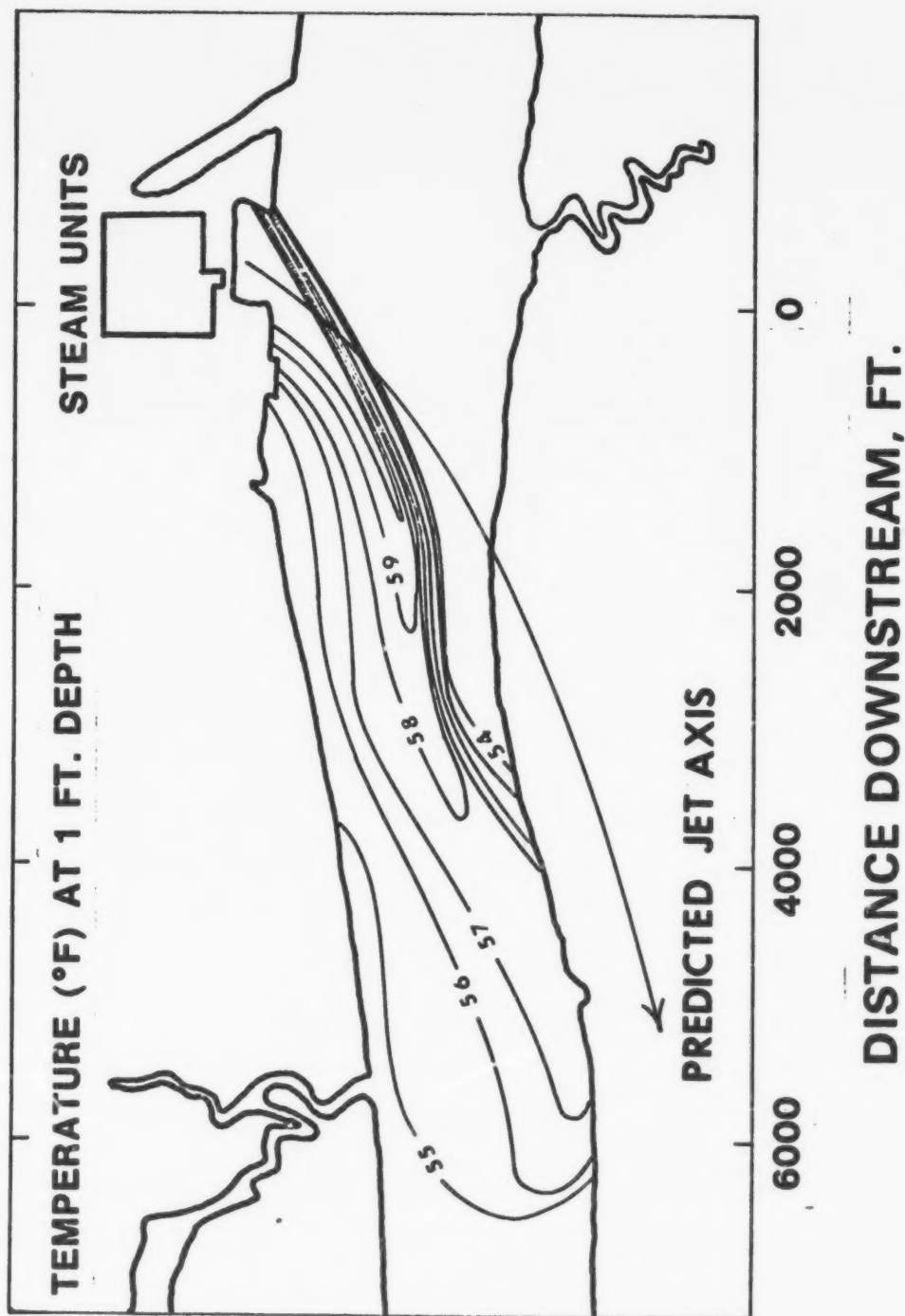


FIGURE 7 - PREDICTED JET AXIS AND OBSERVED TEMPERATURE CONTOURS

Discussion of Results

The observed temperature and geometry values are compared to the predicted values in Figures 5, 6 and 7. The selected value of the entrainment coefficient $E = 0.09$ is also an observed, or apparent, value which must be compared to empirically determined values found in the literature.

The observed temperature rise deviates from the predicted value near the jet discharge by about 2°F and far downstream by about 1°F . The values of E could be adjusted to give a better fit, but this is not felt warranted at the present time.

The values of the jet width are observed in Figure 6 to be greater than predicted. Examination of Figure 7 shows that the temperature contours on the downstream (relative to the ambient current) side of the jet are skewed considerably, resulting in a greater width than predicted. This distortion is felt to be due to the pressure gradient across the jet, a phenomenon that the present model does not consider.

The location of the jet axis is not satisfactorily predicted as shown in Figure 7. The present model does not consider the pressure gradient across the jet, which apparently causes a much greater deflection than predicted.

The entrainment coefficient $E = 0.09$ differs from values found in the literature. Fan (1967) reports values on the order of 0.45 for a round buoyant jet discharged vertically into a uniform ambient current. Keffer and Baines (1963) report values of the entrainment coefficient which vary along the jet axis from 0.3 to 1.6 for air-in-air jets subject to a steady cross-wind. Zeller (1967) presents values which vary from

0.064 to 0.496, not along the jet axis, but from one two-dimensional surface jet to another. The value of $E = 0.09$ is not unreasonable for this field site, however, because the relatively narrow width of the river (compared to the size of the jet) inhibits the spreading of the jet.

SUMMARY AND CONCLUSION

A preliminary analysis of heated discharges has been made. The model presented predicts the lateral and longitudinal distribution of heat based on the assumption that the heated discharge has the characteristics of a two-dimensional surface jet deflected downstream by the receiving water body. Comparison is made between the prediction model and data obtained at T.V.A.'s Widows Creek Steam Plant. This comparison indicates that the present model predicts within 1 or 2°F the decrease in temperature along the jet axis but does not accurately predict the location of the jet axis.

The present analysis indicates that future work, which is already underway, should consider additional factors. Prediction of the jet axis location can be improved by considering the pressure gradient across the jet, perhaps by using a drag coefficient such as used by Fan (1967). Such an approach will require evaluation of an added coefficient. More data must be compared to the temperature prediction to accurately determine the value of the entrainment coefficient for field sites. The effect on the temperature distribution of changing the initial conditions - temperature rise, velocity ratio, and width - should be studied.

The effect of changing the initial angle to less than 90° on the zone of flow establishment should be considered. Added considerations are necessary for this initial zone. The present derivation assumes a uniform temperature and velocity distribution at the point of discharge. This may not be valid for the discharge channels usually employed. Findings on this initial distribution would affect evaluation of S_e , b_o , and β_o . Finally, the extent of vertical entrainment, which is increased by the shearing force of the jet velocity and opposed by the buoyancy force due to the density difference between the surface jet and the heavier ambient fluid, should also be considered, perhaps as a function of the Richardson Number. Inclusion of the above factors, which will involve laboratory experiments as well as field studies, should improve the prediction model.

Preliminary calculations have indicated some difficulties in performing lab studies with existing facilities. Some results might be obtained using higher ΔT 's ($35-40^\circ\text{F}$), with plant flows only about 1 percent of river flow. Attention is being devoted to the possibility of modifying present facilities to enable meaningful experimentation aimed at evaluation of needed coefficients and other parameters.

LIST OF REFERENCES

1. Ellison, T. H., and Turner, J.S., "Turbulent Entrainment in Stratified Flows", Journal of Fluid Mechanics, 6(1959), pp. 423-448.
2. Fan, L. N., "Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids", W. M. Keck Laboratory of Hydraulics and Water Resources,

California Institute of Technology, Pasadena, California, Report No. KH-R-15 (June 1967).

3. G6rdier, R.L., "Studies on Fluid Jets Discharging Normally into Moving Liquid", St. Anthony Falls Hyd. Lab. Tech. Paper 28, Ser. B, Univ. of Minn. (1959).
4. Jen, Y., Wiegel, R.L., and Mobarek, I., "Surface Discharge of Horizontal Warm Water Jet", Hydraulic Engineering Laboratory, University of California, Berkeley, California, Technical Report HEL-3-3 (December 1964).
5. Jordinson, R., "Flow in a Jet Directed Normal to the Wind", Aero. Res. Council Rep. and Memo No. 3074 (1956).
6. Keffer, J.F., and Baines, W.D., "The Round Turbulent Jet in a Cross-Wind", Journal of Fluid Mechanics, 15(1963), pp. 481-496.
7. Morton, B.R., "On a Momentum-Moss Flux Diagram for Turbulent Jets, Plumes and Wakes", Journal of Fluid Mechanics, 10(1961), pp. 101-112.
8. Morton, B.R., Taylor, G.I., and Turner, J.S., "Turbulent Gravitational Convection from Maintained and Instantaneous Sources", Proceedings of the Royal Society of London, A234(1956), pp. 1-23.
9. Zeller, R.W., "Cooling Water Discharge into Lake Monona", Ph.D. Thesis, University of Wisconsin (May 1967).

SUMMARY OF NOTATION

- a subscript pertaining to ambient fluid
- A ratio of the ambient velocity to the initial jet velocity, U_a/U_o
- b half-width of jet
- C circumference through which entrainment takes place
- dA differential area of jet cross-section

D	initial jet width
E	entrainment coefficient
exp	exponential function
I	initial angle of jet in zone of established flow
M	dimensionless momentum flux
o	subscript denoting initial values
O	origin of the coordinate system (x,y), beginning of zone of established flow
O'	origin of the coordinate system (x', y') point of jet discharge
Ri	Richardson Number of the jet
s	coordinate axis of jet
s' _e	length of zone of flow establishment
S	dimensionless distance along jet axis
S _e	dimensionless length of zone of flow establishment
T	centerline temperature rise
T'	temperature rise at any point in the cross-section
u	jet velocity along the jet axis
U	centerline jet velocity
U _a	ambient velocity
U _o	initial jet velocity
V	dimensionless volume flux
v _i	inflow velocity
x	longitudinal axis in zone of established flow
x'	longitudinal axis from point of jet discharge
X	dimensionless longitudinal axis from point of jet discharge
y	lateral axis in zone of established flow

y'	lateral axis from point of jet discharge
Y	dimensionless lateral axis from point of jet discharge
z	depth of jet
β	angle between jet and ambient current
η	axis perpendicular to s axis
σ	standard deviation

EFFECT OF GEOGRAPHICAL LOCATION ON COOLING POND
REQUIREMENTS AND PERFORMANCE

Principal Investigator: Edward L. Thackston

Research Assistant: Larry Elliott

Project Begun: May, 1969

Scheduled Completion: June, 1970

Critique:

INTRODUCTION

Cooling of condenser water from power stations before discharge will probably be much more common in the future than it is now. Stricter water quality standards, increased pressure from state and federal regulatory agencies, and greater concentrations of heat brought about by larger generating stations are all combining to make this trend inevitable.

Water may be cooled by dry cooling towers, wet cooling towers, or cooling ponds. The dry cooling tower depends almost solely on conduction for heat dissipation, and the wet cooling tower almost solely on evaporation. Both involve high capital costs, although wet cooling towers are considerably cheaper than dry towers.

Cooling ponds dissipate heat by radiation, evaporation, and conduction. By relying less heavily on evaporation, they do not consume as much water as towers. However, by not having a forced draft, either structurally or mechanically induced, they require greater areas. In localities where sufficient area is available, cooling ponds frequently are the cheapest and simplest method for cooling water before discharge or reuse.

The design of cooling ponds is sometimes based on rules of thumb, such as 1 to 2 acres per megawatt of installed capacity, or 75 to 150 BTU of heat loss per hour per square foot (Berman, 1961) coupled with engineering judgment and experience. However, rational design should be based on the total energy budget, since local meteorological conditions can greatly influence the rate of heat transfer, and thus, the size of ponds necessary to produce a given cooling effect.

Many references are available in the literature on the energy budget approach to heat transfer calculations, and some give illustrative examples. However, none provide the engineer with a quick estimate at a specific locality of pond size and performance necessary to make preliminary feasibility determinations, or to check the reasonableness of calculations. This is the purpose of the present investigation. Calculated energy budget data will be presented for sites representing the entire continental United States.

A consultant or a power company may use this data to determine approximate pond sizes necessary to produce a specified cooling effect at a given site; to investigate the effect on pond size of different cooling requirements; to determine the influence of season on pond

performance; to estimate the effect of different geometrical configurations; and to estimate the effect of possible alternate sites.

The engineer for a regulatory agency can use this data as an independent check on the reasonableness and/or adequacy of proposed designs which he is charged with reviewing, by determining or estimating the same parameters of performance.

DATA TO BE PRESENTED

In investigating the feasibility of a cooling pond, or in evaluating the design of a proposed pond, certain questions always need to be considered. Among these are:

- (1) What will be the temperature of the power plant intake?
- (2) What will be the temperature of the cooling pond inlet?
- (3) What will be the temperature of the cooling pond outlet,
for a given pond size?
- (4) What is the limit to which the heated water can be cooled?
- (5) What size pond will be necessary to achieve a certain degree
of cooling?
- (6) What effect will the variability of weather conditions at
a site have on the pond performance? How much will abnormal
heating conditions raise the pond effluent temperature?

Most of these questions can be answered by calculating three parameters - the equilibrium temperature, the heat exchange coefficient, and the pond effluent temperature. All three should be calculated for different times during the year; all three should be calculated for

both "normal" (average) meteorological conditions and "critical" heating conditions (those expected to occur with some predetermined critical frequency); and the pond effluent temperature should be calculated for various pond sizes.

Equilibrium Temperature

The equilibrium temperature is the temperature to which a body of water would eventually come if exposed to constant meteorological conditions. It is, therefore, a function of the particular conditions at a given location. A body of water not at the equilibrium temperature will tend to approach equilibrium asymptotically. The equilibrium temperature will vary throughout the day as the solar radiation, temperature, wind speed, and other meteorological variables vary, and also throughout the year. A very small body of water will vary widely in temperature during the day as it follows the changing equilibrium temperature. However, the heat content of water is so great that the temperature of large bodies of water does not fluctuate greatly during the day. Thus, average daily conditions are reasonably descriptive for large bodies of water and the equilibrium temperature may be calculated on an average daily basis.

The temperature of natural water bodies continually approaches the equilibrium temperature but lags behind any changes. It is usually very close to equilibrium during the summer and winter, but is lower during the spring as the equilibrium temperature rises rapidly, and higher during the fall as the equilibrium temperature falls rapidly.

Surface Heat Exchange Coefficient

An isolated body of water not at equilibrium will approach equilibrium at a rate approximately proportional to the difference between actual surface temperature and equilibrium temperature (the forcing function), and to a rate constant which is a function of meteorological conditions (the heat exchange coefficient). This can be expressed as

$$\frac{\partial H}{\partial t} = -K (T_s - T_e) \quad (1)$$

where H = enthalpy, BTU's,

t = time, days,

K = BTU/ft² - °F

T_s = surface temperature, °F,

T_e = equilibrium temperature, °F.

Equation 1 is not an exact description of the process, because all the heat exchange processes are not true linear functions of temperature, but it is close enough to be descriptive of relative magnitudes and trends. Comparison of the heat exchange coefficient calculated for various seasons, locations, and frequencies of occurrence will provide insight into the relative efficiency of cooling ponds under different conditions.

Pond Effluent Temperature at Standard Plant

Equation 1 may be used to calculate rates of surface heat exchange for given time increments (after calculating K and T_e from average meteor-

ological conditions for that time increment) and applied to the water volume to compute the temperature change. This approach to computing water temperatures has been used extensively by some workers (Duttweiler, 1963; Edinger, 1965, 1968a, 1968b). Because of its simplicity, it is the only approach which can be used in many complex situations of geometry and hydraulics.

Another approach is to compute the heat transfer during a given time increment due to each mechanism of heat exchange and sum them to obtain the total heat gain or loss. An example of this approach is given by Raphael (1962). This approach is more accurate, because the individual expressions for heat transfer do not need to be linearized, but its mathematical complexity limits its application to simple hydraulic configurations, such as plug flow or backmix flow.

Since the object of this work is to compare the influence of location on cooling pond performance, a standard pond configuration is assumed. This standard configuration should be as simple as possible, in order to facilitate comparison of conditions and make them meaningful. Therefore, a completely mixed pond was assumed. For this simple configuration, Raphael's approach (1962), assuming each individual energy component, was used. In addition, this approach allows one to tabulate the heat transfer due to different mechanisms under different conditions, and thereby to determine the effect of meteorological conditions on the individual mechanisms.

The "standard plant" assumed for all cases was of 1,000-megawatt capacity. The flow of cooling water was 1350 cfs, and the temperature

rise through the condensers was 15°F. This is equivalent to a plant efficiency of 37 to 38 percent, and is a function of the amount of heat lost from the boilers, through the stack, etc.

The pond effluent temperature was calculated for 15-foot deep completely mixed ponds of various areas for each month at each site, under both "normal" and "critical" meteorological conditions. The data will be presented as "net plant temperature rise", that is, 15°F minus the cooling effect of the pond. For simplicity, the intake temperature is assumed to be the equilibrium temperature; therefore, the pond effluent temperature will be equilibrium plus net plant rise.

METHODS OF CALCULATION

Heat Budget

The net, or total, surface heat exchange, H_t , of a body of water is

$$H_t = H_s + H_a + H_b + H_e + H_c \quad (2)$$

where H_s is the absorbed solar radiation, H_a is the absorbed longwave atmospheric radiation, H_b is the longwave back radiation of the water body to space, H_e is the heat lost by evaporation and H_c is the heat gained or lost by conduction. The individual terms will be defined so that they are positive when heat is being gained by the water body and negative when heat is being lost by the water body. Since all the signs in Equation 2 are positive, the same convention will hold for the net surface heat exchange, H_t .

Calculation of individual components of the heat budget generally

follows the procedures outlined by Raphael (1962). Much of his methodology was in turn derived from the Lake Hefner Studies of the U.S. Geological Survey reported by Anderson (1954). Certain modifications to Raphael's procedure had to be made, however, to adapt it to machine computation. The calculation procedure was designed to require only the standard information tabulated by the weather bureau - temperature, relative humidity, wind speed, and cloud cover, plus the location of the site and the time of year.

Solar Radiation - The altitude of the sun above the horizon was calculated from the equation

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \quad (3)$$

where α is the solar altitude, ϕ is the latitude of the site, δ is the declination of the sun, and h is the hour angle of the sun which is positive before noon and negative after noon.

An equation for δ was fitted to data from a current solar ephemeris by non-linear least squares methods (Marquardt, 1963; Thackston et al, 1967). The equation is

$$\delta = -23.28 \cos \left[(2\pi \text{ day}/365) + 0.164 \right] \quad (4)$$

where day is the day of the year.

Raphael tabulated the total radiation (direct solar radiation plus diffuse, or sky, radiation) on a horizontal surface as a function of solar altitude, taken from the tables prepared by Moon (1940) from U.S. Weather Bureau data.

Reflected solar radiation is a function of solar altitude, being greatest at the low altitudes. It is also a function of sky condition, being greatest for clear skies than for overcast skies at low solar altitudes, and the reverse at high solar altitudes. However, the differences are negligible except at low solar altitudes, where the total radiation is very small anyway, and at high solar altitudes, which are rarely reached. Therefore the curve of average reflectivity as a function of solar altitude was applied to the total radiation tabulated by Raphael to obtain the net absorbed radiation as a function of solar altitude. A simple polynomial was fit to the data by nonlinear least squares methods to produce the equation

$$H_o = 2.044\alpha + 0.1296\alpha^2 - 0.0019\alpha^3 + 0.0000076\alpha^4 \quad (5)$$

where H_o is the absorbed solar radiation for clear sky in BTU per square foot per hour. The fit of the equation to the data is shown in Figure 1. The absorbed solar radiation for other sky conditions was calculated from the equation

$$H_s = (1 - 0.0071 C^2) H_o \quad (6)$$

where H_s is the actual absorbed solar radiation, and C is the cloud cover, in tenths of sky.

The procedure described above will calculate only the instantaneous radiation at a particular time. The instantaneous radiation may be assumed to represent the average radiation over a given time increment, but above an increment of three or four hours, the accuracy is unaccep-

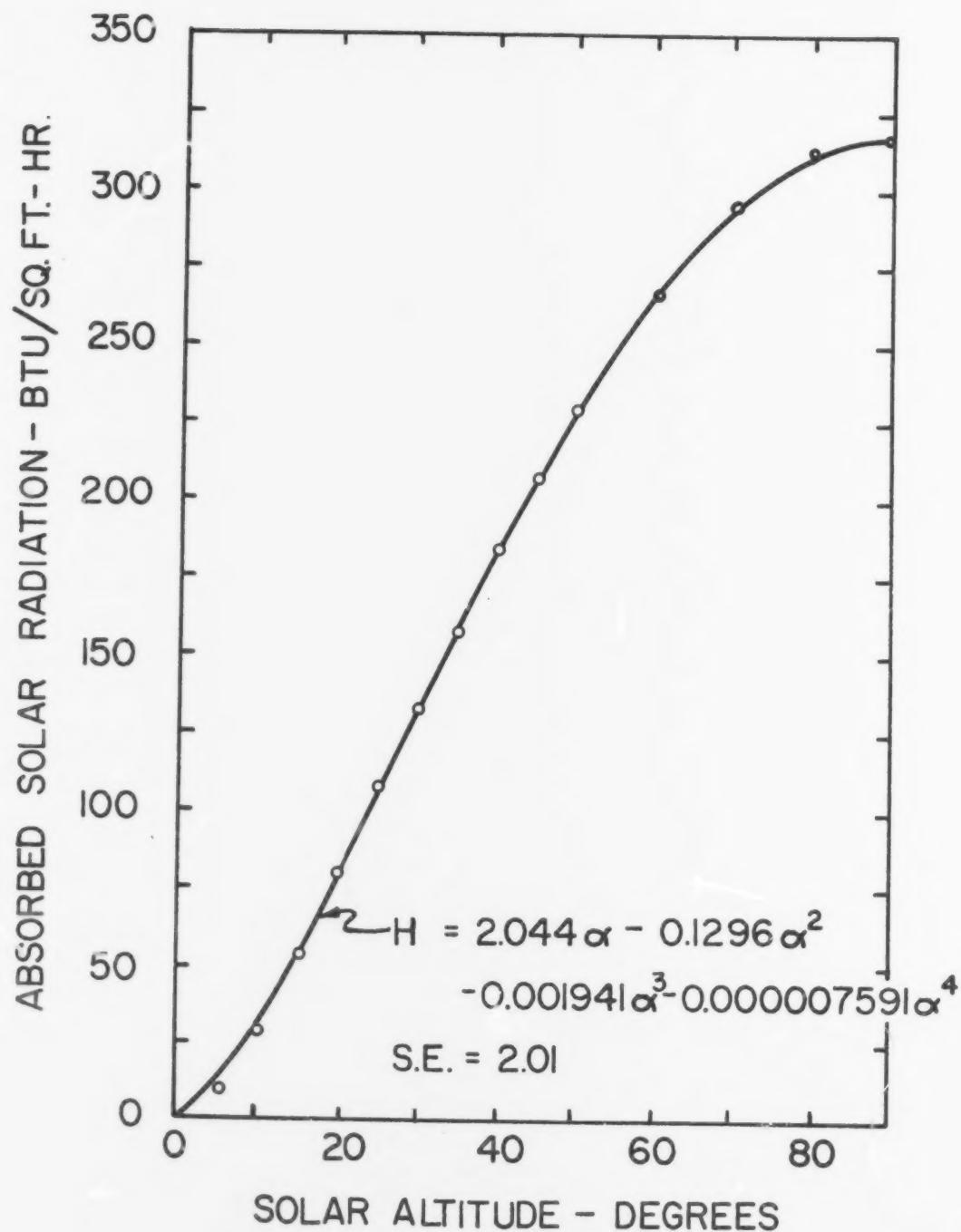


FIGURE 1 - ABSORBED SOLAR RADIATION AS A FUNCTION OF SOLAR ALTITUDE

table, due to the cyclic variation of radiation throughout the day. For longer averaging periods, a different procedure is required. Since this project used the day as the working time period, values of total daily radiation were computed for every tenth day of the year for every degree of latitude from 25° to 46° . The radiation intensity was computed by the procedure outlined above for every six minutes throughout the day and the total daily radiation was obtained by numerical integration. The total was divided by 24 to obtain average daily radiation values in BTU per square foot per hour. For each latitude, an equation was fit to the calculated values by non-linear least squares procedures. The resulting equations are tabulated in Table 1. An example of the fit of three of the equations to the calculated data is shown in Figure 2. The equations were all inserted into the computer program for the heat budget, along with a procedure to select the equation for the latitude closest to the latitude of the site. The program also included provisions for calculating the instantaneous solar radiation, if conditions at a particular hour are desired.

Atmospheric Radiation - Longwave atmospheric radiation is a function of many variables, including the distribution of temperature, moisture, carbon dioxide, ozone and other constituents throughout the entire air column over a site. However, since these data are not normally available, Anderson (1954) proposed the following empirical relationship:

$$H_a = \sigma \eta (T_a + 460)^4 (1 - \omega) \quad (7)$$

in which H_a is the longwave atmospheric radiation in BTU/square foot per

TABLE 1.

EQUATIONS FOR AVERAGE DAILY ABSORBED SOLAR RADIATION (BTU/Sq Ft-Hr)

Latitude	Equation	Standard Error
26	$H_s = 80.155 - 29.207 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.679]$	2.76
27	$H_s = 79.371 - 30.236 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.713]$	2.40
28	$H_s = 78.566 - 31.219 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.710]$	2.33
29	$H_s = 77.604 - 32.145 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.740]$	2.10
30	$H_s = 76.655 - 33.156 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.728]$	2.02
31	$H_s = 76.041 - 34.133 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.694]$	2.21
32	$H_s = 75.060 - 35.194 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.737]$	1.85
33	$H_s = 74.046 - 35.938 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.734]$	1.61
34	$H_s = 73.161 - 36.834 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.727]$	1.52
35	$H_s = 72.248 - 37.699 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.738]$	1.32
36	$H_s = 71.390 - 38.598 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.721]$	1.32
37	$H_s = 70.394 - 39.413 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.730]$	1.07
38	$H_s = 69.350 - 40.188 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.741]$	0.86
39	$H_s = 68.362 - 40.982 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.739]$	0.73
40	$H_s = 76.281 - 41.706 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.742]$	0.61
41	$H_s = 66.240 - 42.442 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.736]$	0.58
42	$H_s = 65.197 - 43.128 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.740]$	0.54
43	$H_s = 64.113 - 43.788 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.739]$	0.63
44	$H_s = 63.010 - 44.471 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.739]$	0.76
45	$H_s = 61.911 - 45.020 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.740]$	0.93
46	$H_s = 60.782 - 45.639 \times \sin[2 \times 3.14159 \times \text{day}/366. + 1.735]$	1.16

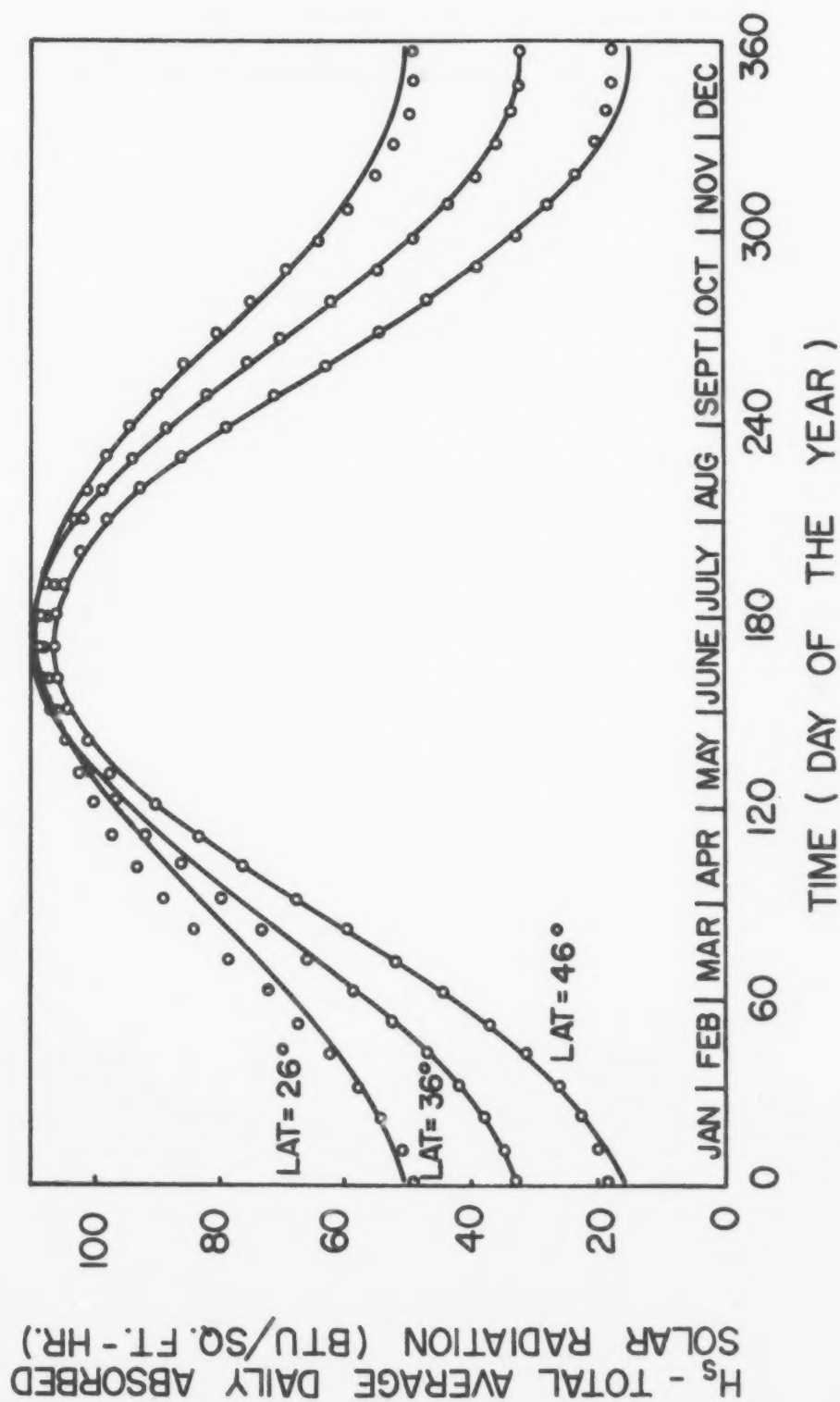


FIGURE 2 - AVERAGE DAILY ABSORBED RADIATION

hour; σ is the Stephan-Boltzmann constant = 1.714×10^{-9} BTU/hr. - sq. ft. - R^4 ; η is a constant which is a function of the height and type of cloud cover and the atmospheric vapor pressure, e_a , in inches of Hg; T_a is the air temperature, in $^{\circ}\text{F}$; and ω is the reflectivity of the water surface, usually taken as 0.03. Raphael converted Anderson's figures and data to a single graph of η vs. e_a , with straight lines representing various values of cloud cover.

This graph was adapted for machine computation by writing an equation of the form

$$\eta = a + b e_a \quad (8)$$

for each value of cloud cover, and instructing the computer to pick the correct equation, based on the value of cloud cover read as data.

The vapor pressure of the air is a function of the relative humidity, R , and the saturated vapor pressure. It is equal to the saturated vapor pressure at the dew point, or wet bulb temperature. The wet bulb temperature, T_{wb} , in $^{\circ}\text{F}$, may be calculated from the relative humidity and air temperature by the equation

$$T_{wb} = (0.655 + 0.36 R) T_a \quad (9)$$

An equation for the saturated vapor pressure, e_s , was obtained by fitting an exponential equation to values of e_s and temperature by the non-linear least squares procedure. The resulting equation, for e_a in inches of mercury, is

$$e_a = \exp [17.62 - 9501/(T_{wb} + 460)] \quad (10)$$

The fit of this equation to the data is shown in Figure 3.

Since the reflectivity of the water surface to longwave radiation is 0.03, the absorbed longwave radiation can then be calculated as

$$H_a = 1.66 \times 10^{-9} \eta (T_a + 460)^4 \quad (11)$$

Back Radiation - Back radiation from the body of water to space is calculated as

$$H_b = -0.97 \sigma (T_w + 460)^4 \quad (12)$$

where H_b is in BTU per square foot per hour, 0.97 is the emissivity of the water surface, and T_w is the temperature of the water surface, in $^{\circ}\text{F}$.

Evaporation - Evaporation is calculated from the formula

$$H_e = -C U (e_w - e_a) \quad (13)$$

where C is an empirical constant which depends on the size, shape, and exposure of the water body, and on the location of the wind speed measurement, and varies from stream to reservoir conditions. U is the wind speed in miles per hour, e_w is the saturated vapor pressure of the air at the temperature of the water surface, in inches of Hg, and e_a is the actual vapor pressure in inches of Hg.

Equation 10 was used to calculate e_w by substituting T_w for T_{wb} . C was set equal to 13.9 for this study. This is approximately equal to the coefficient determined from the Lake Hefner studies, adjusted for

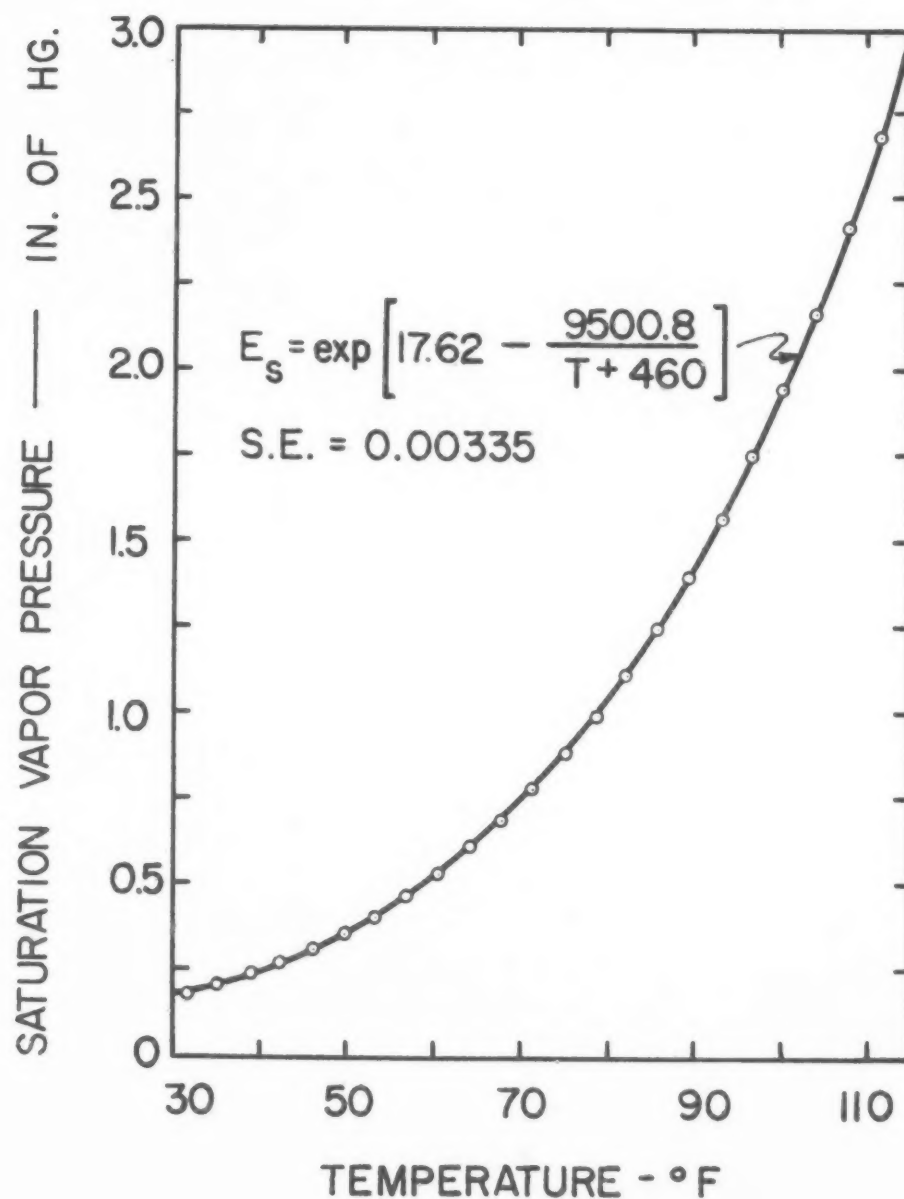


FIGURE 3 - EFFECT OF TEMPERATURE ON VAPOR PRESSURE

the units used.

Conduction - Heat conducted through the water surface was calculated as

$$H_c = 0.00543 U P (T_a - T_w) \quad (14)$$

where P is the atmospheric pressure in inches of mercury, which is calculated as

$$P = \frac{29.92}{\exp \left[\frac{32.15 E}{1545 (T_a + 460)} \right]} \quad (15)$$

in which E is the elevation of the site in feet.

EQUILIBRIUM TEMPERATURE

The equilibrium temperature was determined by calculating H_t for an assumed equilibrium temperature and then correcting it according to Equation 1. In this case, $T_s - T_e$ becomes the correction to the assumed temperature. The heat exchange coefficient is calculated for each iteration as described below. The calculation procedure converges rapidly, and when the correction became less than 0.1°F , the calculation was terminated. When this occurred, H_t was generally less than ± 3.0 BTU per square foot per day.

This method of calculation, while indirect and slower than the direct calculation proposed by Edinger and Geyer (1965), is more accurate because it avoids the approximations necessary in their procedure. They were forced to convert the expressions for heat loss due to back

radiation and for vapor pressure to linear equations in order to solve the total heat budget equation for T_e .

HEAT EXCHANGE COEFFICIENT

The expression given by Edinger and Geyer for the heat exchange coefficient is

$$K = 15.7 + (0.01025 + \beta) (333 U) \quad (16)$$

when converted to the units used in this paper, where β is the slope of the vapor pressure vs. temperature curve. Certain approximations had to be made in order to define a linear heat exchange coefficient. However, Edinger and Geyer made a further linearization of the vapor pressure curve into segments of straight lines which introduces further inaccuracy and computational difficulty. This was found to be unnecessary in this study.

The slope of the vapor pressure curve can be found exactly at any temperature by differentiating Equation 10 with respect to temperature. This gives

$$\beta = \frac{9501}{(T + 460)^2} \exp \left[17.62 - \frac{9501}{(T + 460)} \right] \quad (17)$$

In this study, T_e and K were computed at the same time. A new K was computed for each iteration by Equation 16, using the previously determined temperature. The final K is computed after T_e has been determined within 0.1 °F.

AMOUNT OF COOLING THROUGH POND

The amount of cooling through ponds of various sizes receiving discharge from the standard plant was computed for each month of the year at each site. The values of meteorological data used were monthly averages. Solar radiation was computed based on the midday for each month.

In the calculation procedure, the pond was started at either an assumed temperature or the final temperature of the previous month. It was then subjected to constant meteorological conditions representative of that month until the effluent temperature stabilized. This was taken as the average effluent temperature for that month, and the program proceeded to the next month.

The calculation procedure closely followed that of Raphael. During any calculation period, the water temperature was assumed to be constant at the value calculated for the end of the previous period for the purposes of calculating surface heat transfer.

SOURCE OF METEOROLOGICAL INFORMATION

Meteorological information used in calculating the terms in the heat budget was taken from the U.S. Weather Bureau's publication, "Local Climatological Data, Annual Summary with Comparative Data", for the various stations.

This publication presents the monthly averages and extremes of temperature, degree days, relative humidity, wind speed, cloud cover, and totals for precipitation data for the current year, and compares

them with means and extremes.

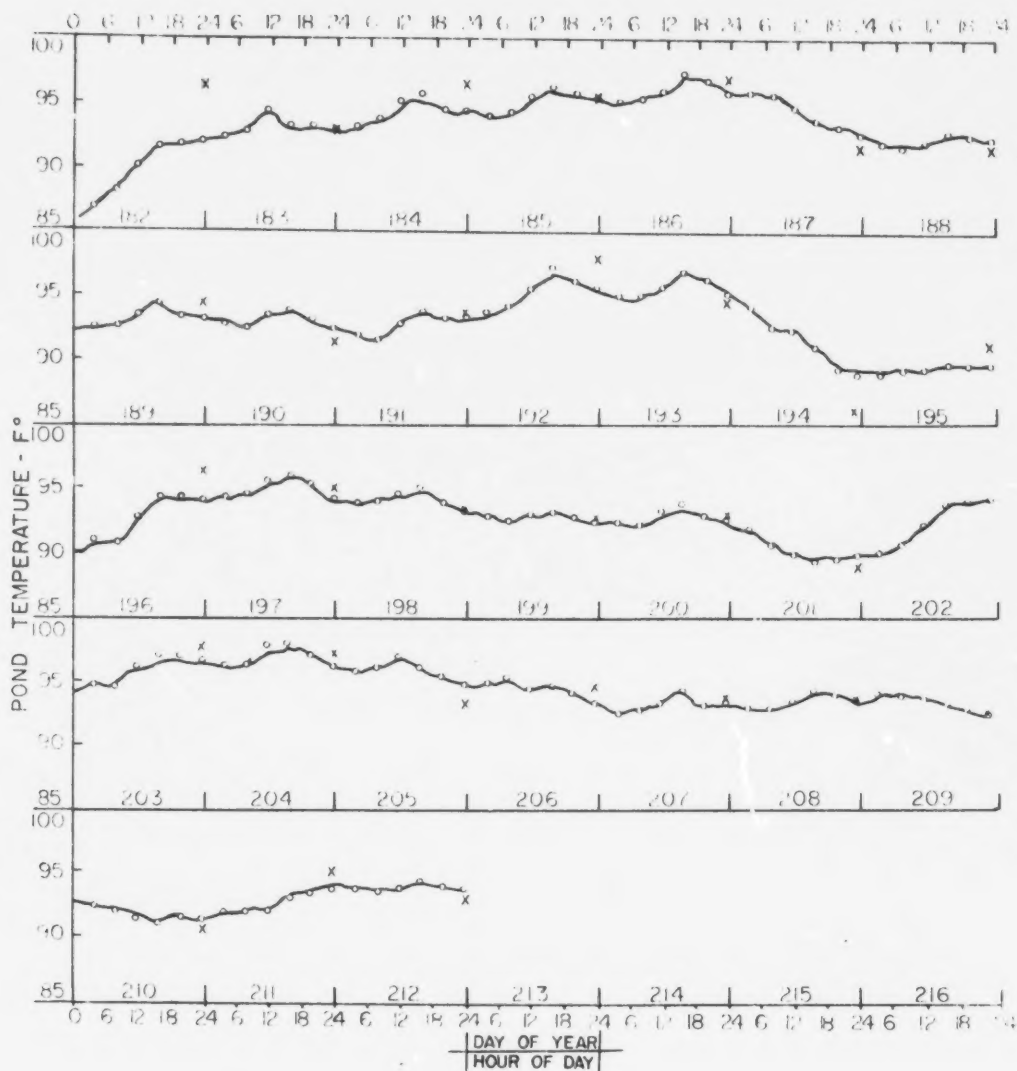
The extreme conditions have not been determined yet, but will be derived from statistical analysis of the monthly average data given in the annual summaries for the same period of record. The value used will be the 5-percent value (the monthly average exceeded, on the average, once in 20 years). The 5-percent high values of temperature and relative humidity and the 5-percent low values of wind speed and cloud cover will be used in order to obtain conditions conducive to maximum heating. Reference to another Weather Bureau publication, "Statistical Summary of Hourly Observations", shows that, in general, these conditions tend to occur together at many stations.

RESULTS OF PRELIMINARY INVESTIGATIONS

Effect of Time Averaging

In order to see if data averaged over periods of hours or days would produce pond effluent temperatures which matched average pond effluent temperatures calculated from hourly meteorological information, a test case was run. The data used was that for July, 1963, at Nashville, Tennessee. The pond influent was assumed to 100°F, and, in order to insure considerable fluctuation in mixed water temperatures for comparison, a relatively small, shallow pond was assumed. It had a detention time of one day and a depth of 9 feet.

The results of the study are shown in Figure 4. The solid line is the result of using hourly observations and calculation periods. The



WEATHER INFORMATION FOR JULY, 1963 - NASHVILLE, TENNESSEE

EQUILIBRIUM TEMPERATURE = 85°

STREAM TEMPERATURE = 85°

CONDENSER RISE = 15°

POND INFLUENT = 100°

POND DETENTION TIME = 1 DAY

POND DEPTH = 9 FEET

— 1-HR AVERAGE DATA
 ○ ○ ○ ○ ○ 4-HR AVERAGE DATA
 x x 24-HR AVERAGE DATA

FIGURE 4 - EFFECT OF TIME AVERAGING ON POND TEMPERATURE

circles are the result of using a calculation period and data averaged over 4 hours. The point is plotted at the end of the 4-hour averaging period. The crosses are the result of using a calculation period and data averaged over a 24-hour period.

The 4-hour average points follow the "true" (one-hour) line almost perfectly. The 24-hour average points show more deviation, but no consistent trend of deviation. The chief effect seems to be the apparent tendency of the 24-hour average to overcorrect to a too high value following a too low value, or vice-versa, during periods when warming trends are followed by cooling trends, or vice-versa. This is partly due to the fact that the 24-hour point is plotted at midnight (the end of the averaging period) and changes in the trend of the line generally follow the normal diurnal pattern of highs during early afternoon and lows during early morning.

The figure shows, however, that there is no consistent over or under-estimation of average temperatures for Nashville by using averaging periods which ignore the diurnal cycle. This is important because the 24-hour diurnal cycle is by far the most influential meteorological characteristic of the factors affecting surface heat exchange. Once it has been determined that neglecting the diurnal cycle will cause little or no consistent error in computing average effluent temperature from large ponds of several days detention time, it is relatively easy to move to monthly average values of meteorological data. This is so because the next shortest cycle is the yearly cycle, whose influence is preserved by using monthly averaging periods. It can be seen that there is much more similarity between daily averages and monthly

averages than between hourly averages and daily averages. This finding will be checked for other climatic conditions.

Effect of Pond Depth

Pond effluent temperatures were calculated for various pond surface areas and various meteorological conditions. The only pond characteristic (other than hydraulic behavior, which is theoretically comparable) which was not varied was the depth. In order to determine if the depth of the pond had a significant effect on the outlet temperature, the effluent temperature for Nashville, Tennessee, was calculated for pond depths of both 15 and 25 feet. The results are plotted in Figure 5. Based on this data, the depth is not a critical variable, as the greatest difference in the pond effluent temperature caused by a 67 percent increase in depth was approximately 0.1°F , a negligible difference probably caused by rounding errors in the computer program. Depth should have no effect because, as depth of a completely mixed pond is increased, so is the flow-through time. All depths are sufficiently deep that all energy is absorbed in the water column and does not reach the bottom sediments.

Effect of Season

Figure 5 also shows a decided effect of season on the amount of cooling taking place in the pond. There is a 2-degree difference in the pond cooling effect between summer and winter. Although, in this example, all sizes of ponds tested produced 2 degrees more cooling

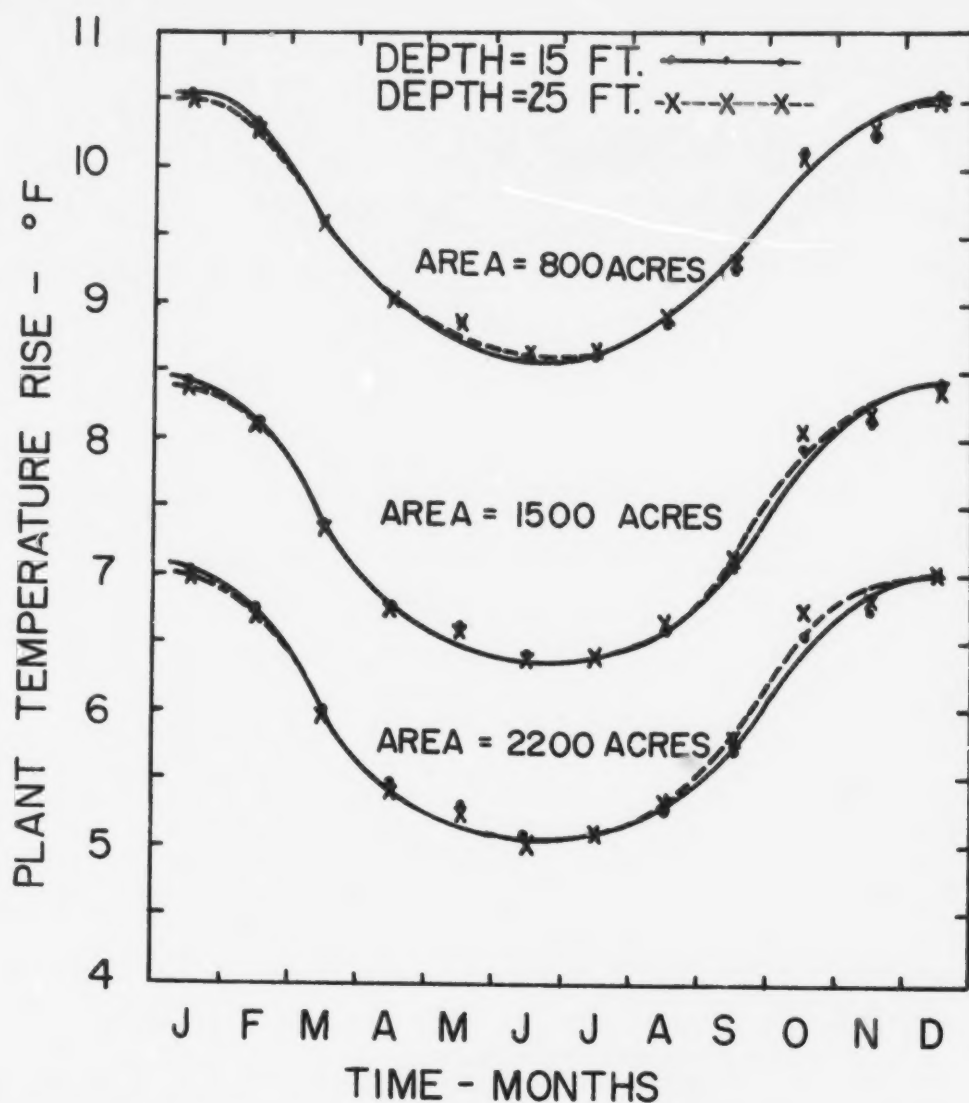


FIGURE 5 - EFFECT OF DEPTH OF COMPLETELY MIXED POND ON AMOUNT OF COOLING, NASHVILLE, TENNESSEE

during the summer, the actual pond effluent temperature would, of course, be higher in the summer than in the winter, because the plant intake temperature would be higher. As mentioned earlier, the pond effluent temperature in this study can be determined by adding the plant temperature rise to the equilibrium temperature.

The extra cooling which occurs during the summer is caused by (or described by) the increase in the heat exchange coefficient during the summer. As shown by Equation 16, K is a direct function of β , and Equation 10 and Figure 3 show that β rises with increasing water temperature. This more than offsets the slight decrease in wind speed during the summer noted at most stations and results in a net increase in K .

Effect of Pond Size

Also illustrated in Figure 5 is the decided effect of pond surface area on cooling. For instance, an 800-acre pond will effect 6.5°F of cooling during June, and a 1500-acre pond will effect 8.5°F of cooling. However, it can be easily seen that successive size increases will have less and less effect as the plant temperature rise approaches zero. This is expected, since theoretically, it would take a pond of infinite size to cool the heated water to the equilibrium temperature. By plotting the plant temperature rise vs. surface area for various seasons or critical times, the planner can easily get a quick idea of what size pond would be necessary to meet given objectives in a given situation. This type plot is illustrated in Figure 6.

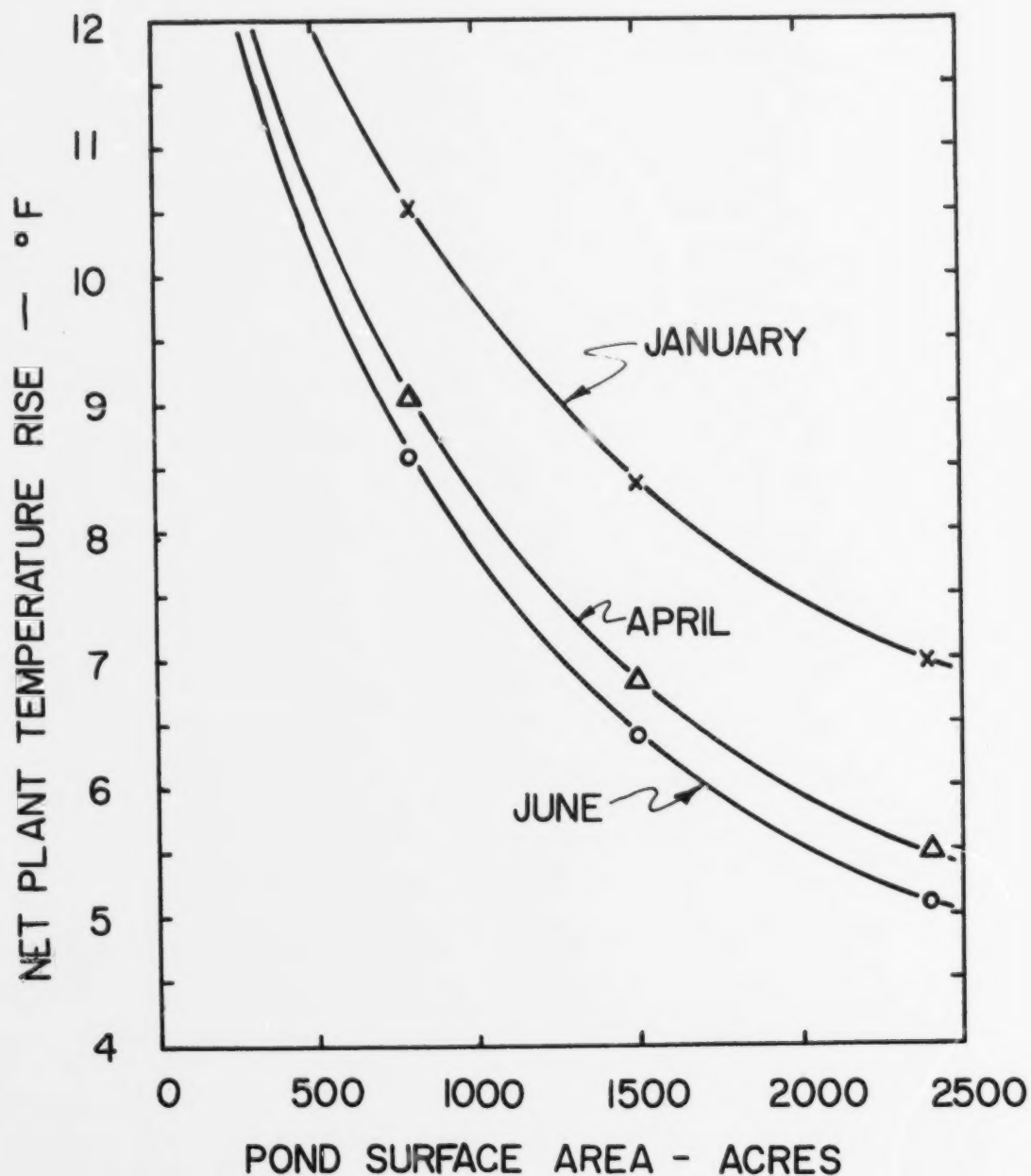


FIGURE 6 - EFFECT OF POND SURFACE AREA ON AMOUNT OF COOLING FOR VARIOUS SEASONS, NASHVILLE, TENNESSEE

Results for Each Station

The meteorological information used for each station will be tabulated on a standard form as shown on Figure 7. All the input necessary for the computer program is contained on this sheet. The data for each station will be plotted on a standard graph as shown on Figure 8. The data used and results from each station will be included in the Technical Report on this project to be published when the project is completed. There will be approximately 75 stations analyzed in all. Five stations in addition to Nashville have been analyzed and the results are shown in Figures 9 - 13.

ANALYSIS OF RESULTS

Since the calculations for this project have not been completed, only a short discussion of how the results will be summarized and presented would be appropriate.

It is planned to summarize the results as a series of maps of the U.S., one map for each of several possible parameters of interest, with lines connecting points of equal values of the parameter, similar to isotherms. Some of the possible parameters which might be presented in this fashion are listed below.

- (1) Highest equilibrium temperature during the year.
- (2) Lowest equilibrium temperature during the year.
- (3) Date on which rising equilibrium temperature passes through a particular temperature, such as a representative fish spawning temperature, in the spring.

WEATHER INFORMATION FOR NASHVILLE, TENNESSEE

MO	NORMAL CONDITIONS					EXTREME CONDITIONS				
	CC	TAIR	HUM	PPT	WIND	CC	TAIR	HUM	PPT	WIND
JAN	7.1	39.0	.71		9.0	5.5	47.0	.84		7.4
FEB	6.7	41.0	.63		9.2	5.2	48.0	.80		7.1
MAR	6.5	49.5	.60		9.9	5.5	59.0	.75		8.2
APR	6.2	59.5	.64		9.4	5.2	64.0	.71		8.2
MAY	5.9	68.3	.68		7.5	4.8	73.0	.75		5.5
JUNE	5.5	76.3	.69		6.7	4.1	82.0	.77		5.0
JULY	5.7	79.4	.75		6.2	4.0	82.0	.79		4.3
AUG	5.3	78.3	.76		5.9	4.0	82.0	.78		4.5
SEPT	5.0	72.2	.76		6.2	3.6	77.0	.80		4.2
OCT	4.6	61.0	.66		6.3	2.4	68.0	.80		5.1
NOV	5.9	48.9	.68		8.2	4.3	57.0	.78		6.0
DEC	6.7	41.0	.69		8.6	5.5	48.0	.81		7.1

LATITUDE = 36° 07'NLONGITUDE = 86° 41'WELEVATION = 590 Ft.

FIGURE 7 - SAMPLE DATA SHEET FOR METEOROLOGICAL INFORMATION

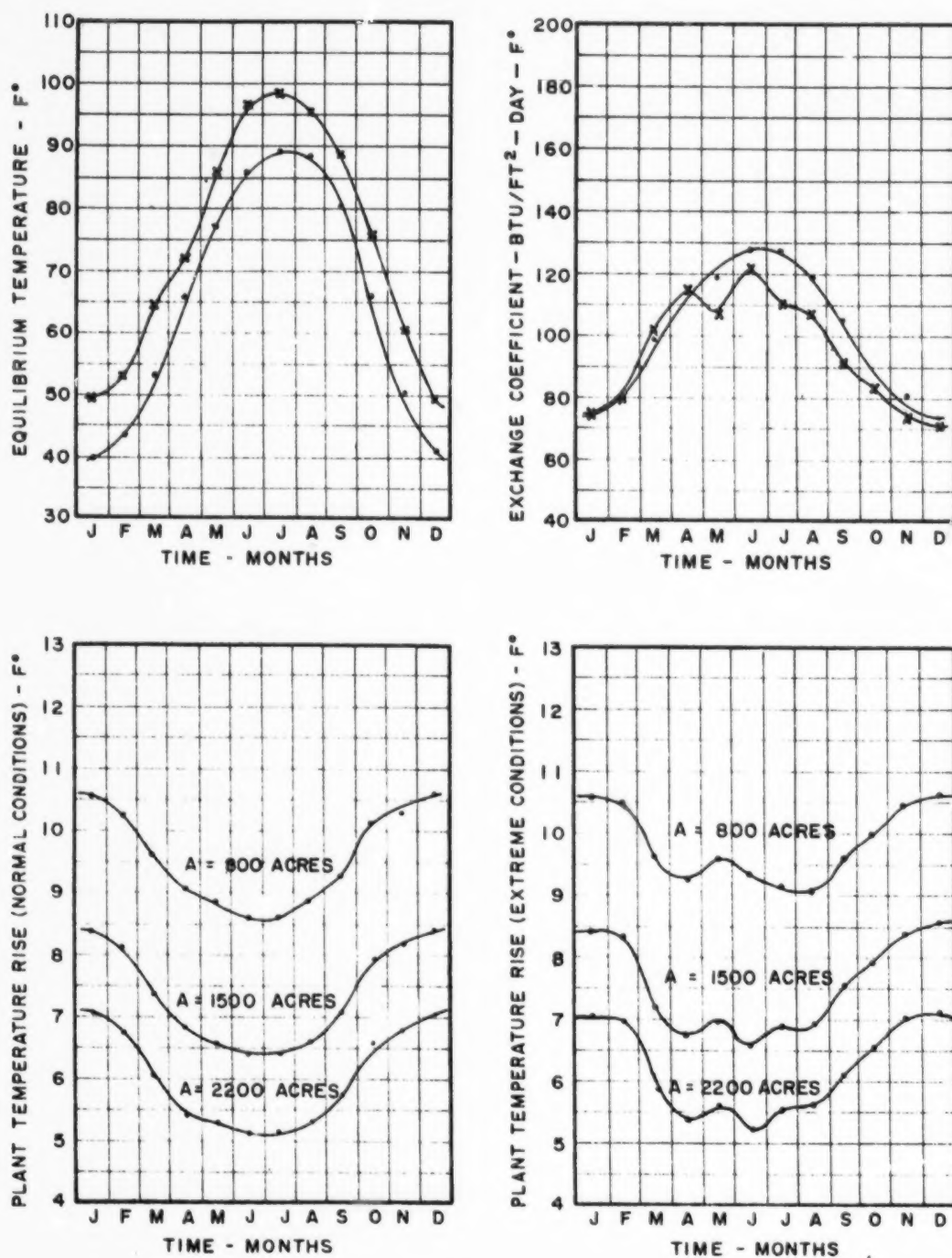


FIGURE 8 - NASHVILLE , TENNESSEE

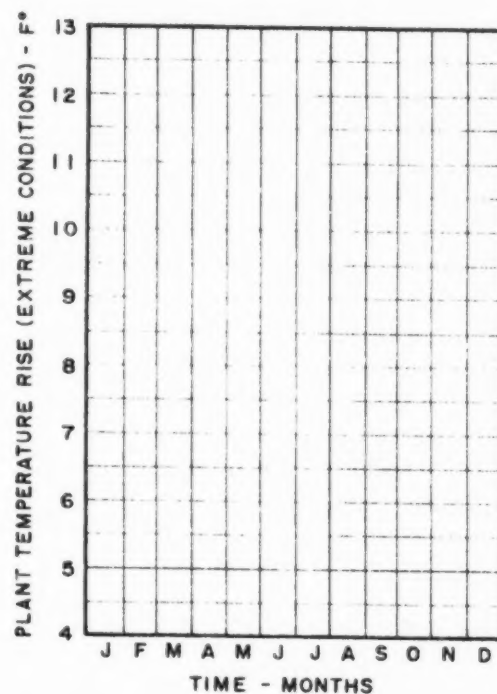
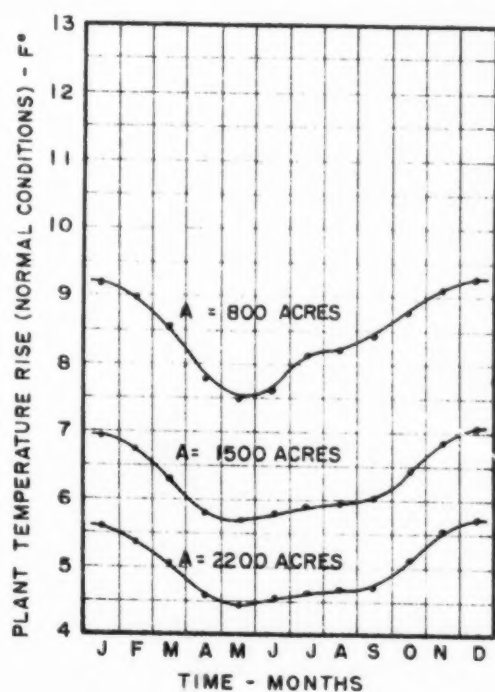
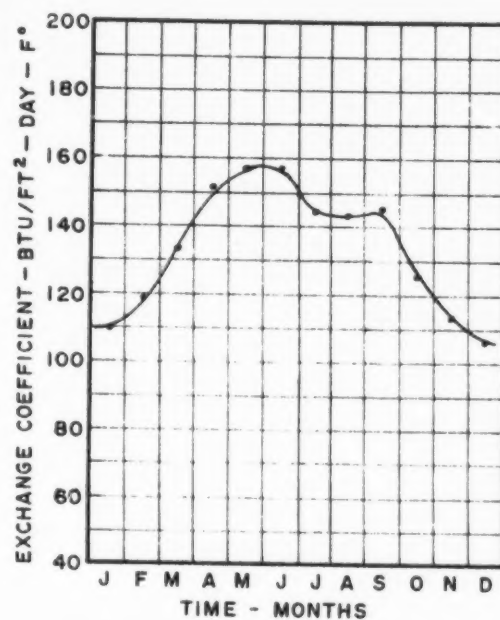
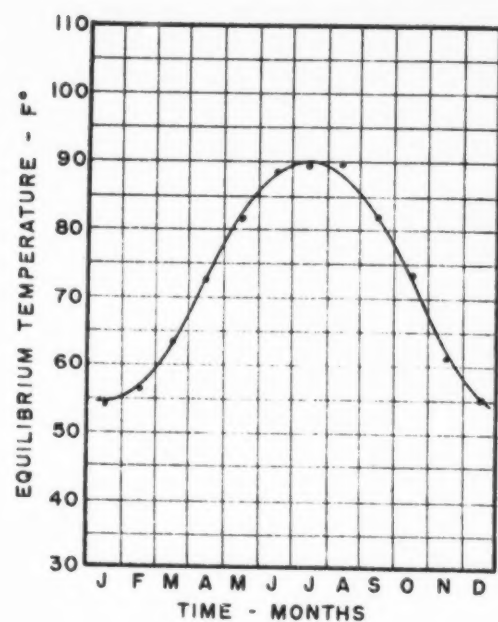


FIGURE 9 - MOBILE, ALABAMA

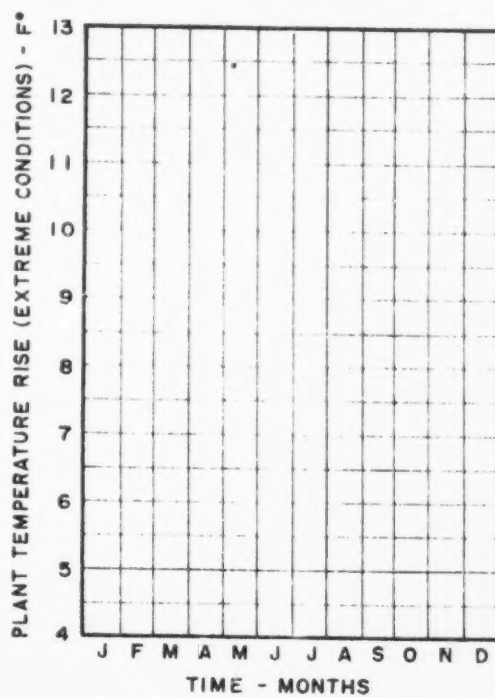
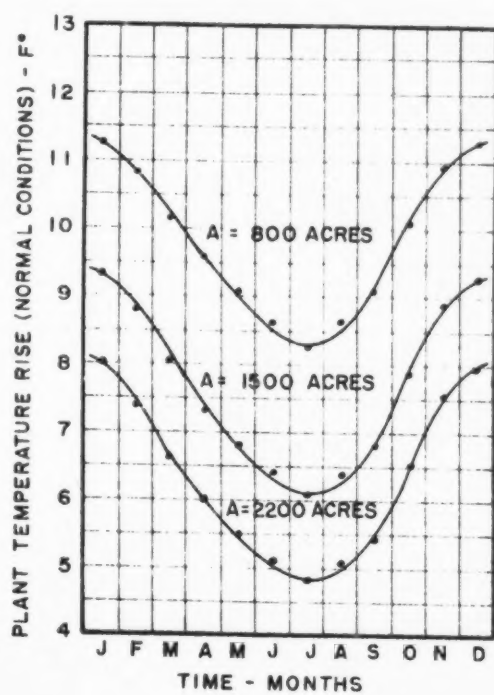
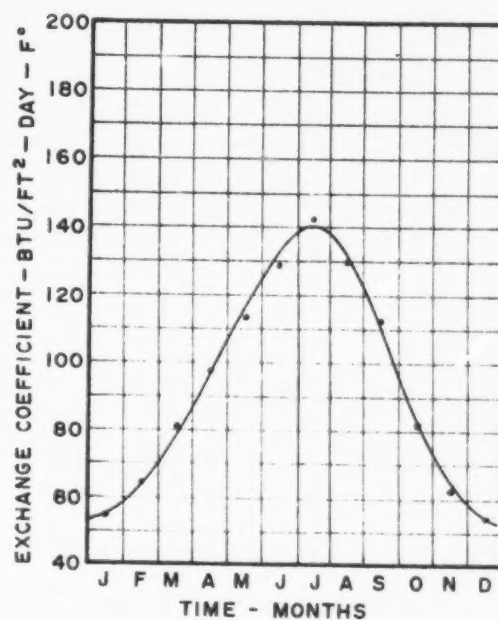
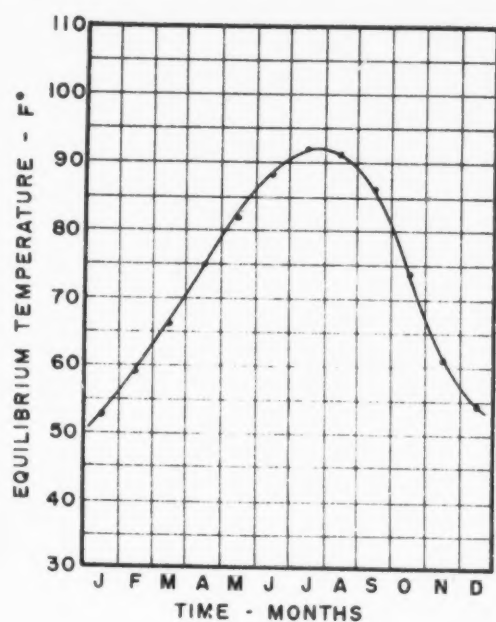


FIGURE 10 - PHOENIX , ARIZONA

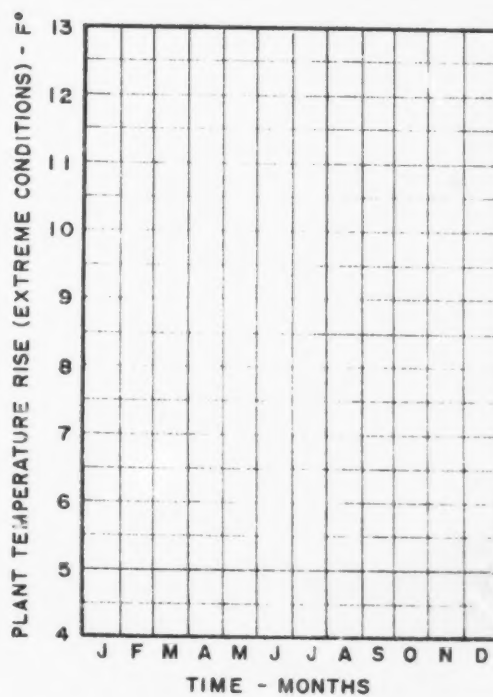
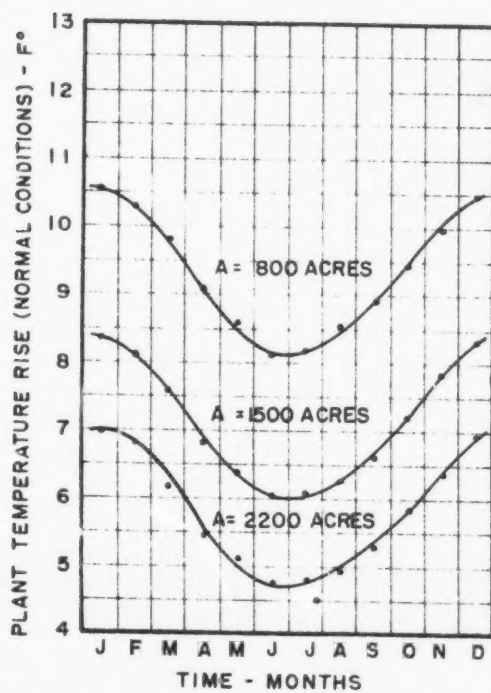
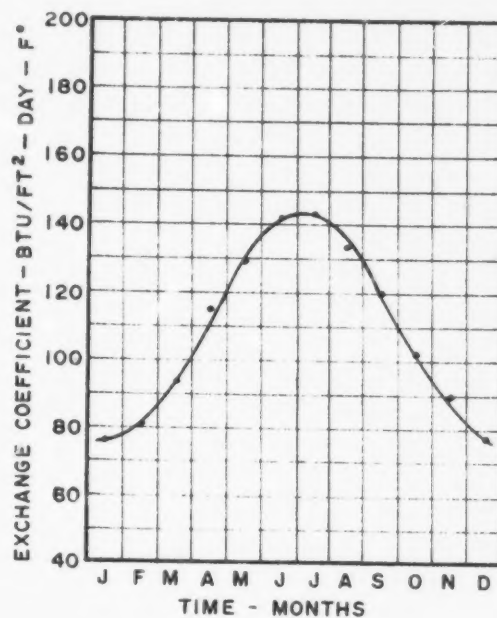
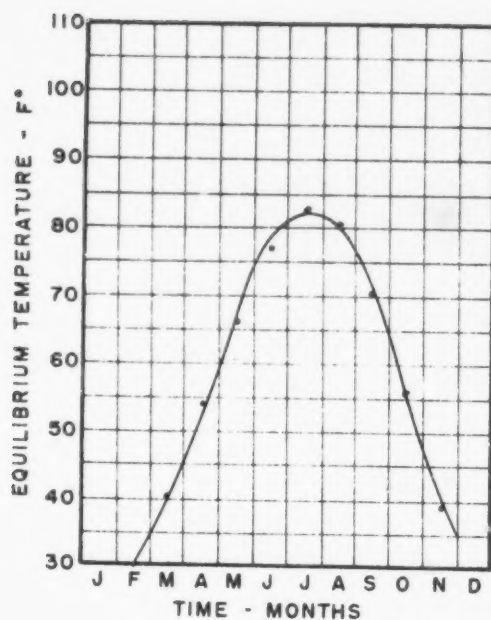


FIGURE 11- CHICAGO, ILLINOIS

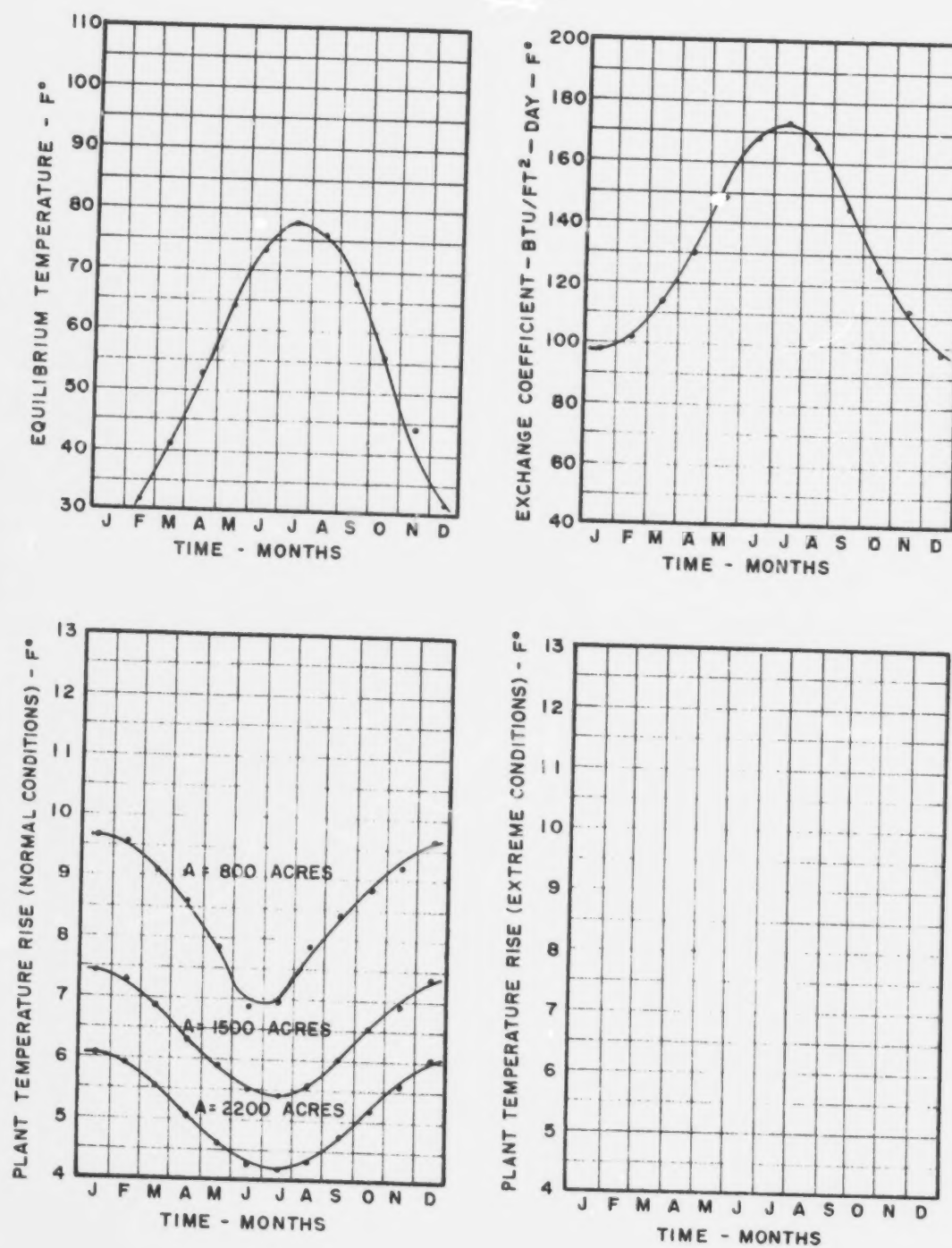


FIGURE 12 - BOSTON, MASSACHUSETTS

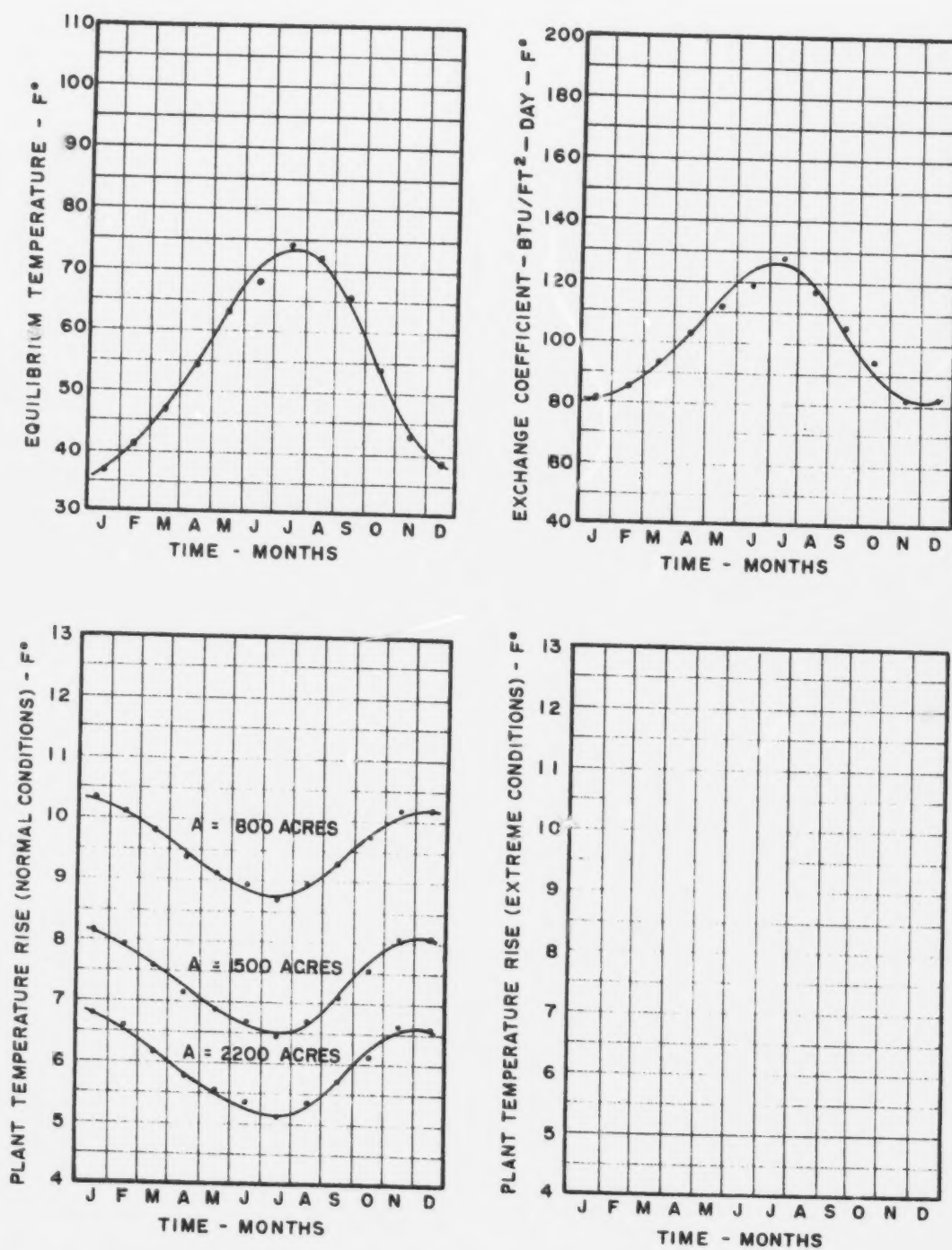


FIGURE 13 - SEATTLE, WASHINGTON

- (4) Length of time equilibrium temperature stays above a certain value during the summer.
- (5) Maximum equilibrium temperature for critical conditions.
- (6) Maximum heat exchange coefficient during the year.
- (7) Minimum heat exchange coefficient during the year.
- (8) Net plant temperature rise for a 1500-acre pond, for June.
- (9) Net plant temperature rise for a 1500-acre pond, for June, critical conditions.
- (10) Pond size necessary to produce 50 percent cooling (7.5°F), for June.
- (11) Pond size necessary to produce 50 percent cooling (7.5°F), for June, critical conditions.

There are many other parameters, some only slight variations of those listed above and some quite different, which could be mapped. Those parameters which have significant variations and a logical enough pattern throughout the country to allow presentation on such a map will be plotted.

RELATION OF COMPLETELY MIXED POND TO PLUG FLOW POND

All calculations for this project have been performed assuming completely mixed ponds. The basic assumption of completely mixed flow is that the pond temperature is uniform throughout, and that anything (such as heat, or a pollutant, or a tracer) added to the pond is "instantaneously" dispersed uniformly throughout the pond. Instantaneous

is very fast, and it would be impossible for a real pond of significant size to behave exactly in this manner. However, it is possible for ponds to approach this condition so that the theoretical and actual dynamic behavior, measured at the outlet, differ by a negligible amount. In such a pond, the condenser water would drop to the uniform pond temperature in a relatively short time, and only a small fraction of the pond volume around the plant would have a temperature higher than the mixed temperature. Conditions conducive to such behavior would include sufficient depth to allow flow to circulate easily in the pond due to the influence of plant discharge and wind, but not so deep as to allow stratification; a surface shape approaching the circular, so the influent can mix easily into all parts of the pond; a discharge located away from the pond shore; and a long detention time.

The other extreme hydraulic condition, exactly opposite to complete mixing, is plug flow. Plug flow implies no mixing at all. Each parcel of influent follows the same path through the pond, utilizes the entire cross-sectional flow area, does not mix with the parcels ahead or behind, and arrives at the outlet in sequence at the exact volumetric detention time. This type of flow is much more difficult to approach exactly in the field than is completely mixed flow, but reasonable approximations can be realized. Conditions which encourage plug flow are long slender channel-like ponds, with the outlet at the opposite end from the inlet, narrow width to decrease wind mixing, high width-to-depth ratios to reduce lateral velocity gradients, and shallow depth and low velocity to reduce vertical velocity gradients. (These conditions are not always mutually consistent, which is part of the problem.)

The plug-flow pond is more expensive to build but provides quicker cooling. This is because the hot water is not initially mixed or diluted with any cooler water, and the driving force for cooling, $T - T_e$, is maintained at the highest possible value at all times.

Edinger and Geyer (1965) show how the area required by each type of pond for a given amount of cooling can be calculated, based on the two solutions for the linear approximation to the heat transfer process (Equation 1). The solution of Equation 1 for a completely mixed pond is

$$\frac{T_m - T_e}{T_o - T_e} = \frac{1}{1 + r} \quad (18)$$

where T_m = the mixed pond temperature (effluent temperature)

T_o = the pond influent temperature (condenser discharge)

T_e = the equilibrium temperature

and in which

$$r = \frac{K A}{\rho c_p Q} \quad (19)$$

where A = the pond surface area

ρ = the water density

c_p = the specific heat of water

Q = the flowrate through the pond (plant pumpage).

The solution of Equation 1 for a plug-flow pond is

$$\frac{T_p - T_e}{T_o - T_e} = e^{-r} \quad (20)$$

in which T_p is the pond effluent temperature at the end of plug-flow pond of surface area A .

The ratio of the net plant temperature rise at the end of a completely mixed pond to that at the end of a plug flow pond is calculated by dividing Equation 18 by Equation 20. The result is

$$\frac{T_m - T_e}{T_p - T_e} = \frac{e^r}{1 + r} \quad (21)$$

The area of a plug-flow pond necessary to produce the same cooling as a completely mixed pond ($T_m - T_e = T_p - T_e$) is given by the relation

$$r_m = e^r - 1 \quad (22)$$

where the only difference between r_m and r_p is the surface area A . Table 2, adapted from Edinger and Geyer, shows the area ratio required for various values of the excess of pond effluent temperature over equilibrium temperature.

Using Table 2, any of the areas determined for a completely mixed pond can be converted to the area of an equivalent plug-flow pond. It should be noted, however, that true plug flow is impossible to attain on such a large scale, due to the inability to eliminate longitudinal mixing in large bodies of water. If a plug-flow type pond is desired, the area required will be somewhat more than that for a perfect plug-flow pond, but less than that required for a completely mixed pond. The behavior of almost all real ponds lies somewhere between the two extremes, depending on pond characteristics. However, the results presented in this report will allow rapid determination of

TABLE 2

RATIO OF AREA REQUIRED BY PLUG-FLOW POND
TO THAT REQUIRED BY COMPLETELY MIXED POND TO PRODUCE
EQUIVALENT COOLING UNDER SAME CONDITIONS

Temperature Excess Ratio $\left(\frac{T - T_e}{T_o - T_e} \right)$	$T - T_e$ (For $T_o - T_e$ of 15°)	Area Ratio $\left(\frac{A_p}{A_m} \right)$
0.8	12°	0.89
0.7	10.5°	0.83
0.6	9°	0.77
0.5	7.5°	0.69
0.4	6°	0.61
0.3	4.5°	0.51
0.2	3°	0.40
0.1	1.5°	0.26

the upper and lower limits of required area. Further study would then be required to complete design of an appropriate pond for a given situation.

REFERENCES

1. Berman, Leo D., *Evaporative Cooling of Circulating Water*, Pergamon Press, New York, New York, 1961.
2. Duttweiler, D.W., "A Mathematical Model of Stream Temperature", Ph.D. Dissertation, The Johns Hopkins University, Baltimore, Maryland, 1963.
3. Edinger, John E., and John C. Geyer, "Heat Exchange in the Environment", Publication No. 65-902, Edison Electric Institute, New York, New York, 1965.
4. Edinger, John E., and John C. Geyer, "Analyzing Steam Electric Power Plant Discharges", Journal of the Sanitary Engineering Division, Am. Soc. of Civil Eng., 94, SA4, August, 1968a.
5. Edinger, John E., David W. Duttweiler, and John C. Geyer, "The Response of Water Temperatures to Meteorological Conditions", Water Resources Research, 4, 5, October, 1968b.
6. Raphael, Jerome M., "Prediction of Temperature in Rivers and Reservoirs", Journal of the Power Division, Am. Soc. of Civil Eng., 88, P02, July, 1962.
7. Anderson, E.R., "Energy-Budget Studies, Water Loss Investigations: Lake Hefner Studies", Professional Paper 269, U.S. Geological Survey, Washington, D.C., 1954.
8. Marquart, D.W., "An Algorithm for Least-Squares Estimation of Nonlinear Parameters", Journal of the Society for Industrial and Applied Mathematics, June, 1963.

9. Thackston, Edward L., J. R. Hayes, and P. A. Krenkel, "Least Squares Estimation of Mixing Coefficients", Journal of the Sanitary Engineering Division, Am. Soc. of Civil Eng., 93, SA3, June, 1967.
10. Moon, Parry, "Proposed Standard Radiation Curves for Engineering Use", Journal of the Franklin Institute, 230, 5, November, 1940.

STATUS OF THE ART AND RESEARCH NEEDS FOR THERMAL POLLUTION

Principal Investigators: Frank L. Parker
Peter A. Krenkel

Research Assistants: Barry A. Benedict
George W. Malaney
James N. Speakman

Project Began: June, 1968

Scheduled Completion: September, 1969

Critique:

The specific objectives of this study were:

1. To compile an exhaustive bibliography on thermal pollution, including the effects of heat on chemical, biological and physical aspects of water quality, the effects of heat on waste assimilation capacity, alternative methods for the dissipation of excess heat from cooling waters, the hydrodynamics of heated water discharges, and the energy balance as related to the dissipation of heat from receiving waters.
2. After intensive review, to select the most meaningful and current references from the bibliography and subject these papers to critical review and summary.
3. To present a report derived from (2) which will contain the following items:
 - a. Discussion of each topic in sufficient detail to give the reader insight into the current stage of development of that topic.
 - b. Discussion of the major research needs in each problem area and an indication of the most fruitful approaches of these needs.

c. Discussion of the existing and potential water quality problems due to heated discharges and their relationship to water pollution control requirements.

The report is now in rough draft form and it is planned to submit each section to a person competent in the material in that section for a general review.

It is anticipated that the final report, in finished form, will be available by November 1, 1969.

INITIAL MIXING OF THERMAL DISCHARGES INTO A UNIFORM CURRENT

Principal Investigators: John E. Edinger,
Edward M. Polk

Research Assistants: Field Crews

Project Began: September 1968

Scheduled Completion: September 1970

Critique: See Attached Report

NOTE: This report was published as Report Number 1 of the National Center for Research and Training in the Hydrologic and Hydraulic Aspects of Water Pollution Control and single copies are available upon request.

RESEARCH ACCOMPLISHMENTS
(PROJECTS NOT SUPPORTED BY GRANT FUNDS)

NEGATIVE BUOYANT JETS IN FLOWING STREAMS

Principal Investigator: Frank L. Parker
Other Professional Personnel: Barry A. Benedict
Research Assistant: Richard Connor
Project Began: March, 1969
Scheduled Completion: June, 1970
Critique:

During the past several decades, much work has been done in an effort to better define the dispersion of a waste which is discharged from a jet or a manifold. However, most of this work has been concerned with the problem of waste water disposal in the ocean or heated effluents into a stream or reservoir. In these cases and in the case of some industrial and domestic wastes discharged into fresh water bodies, these studies were concerned with the property of buoyant plumes.

There are a number of chemical and industrial processes today which produce a waste that is more dense than the ambient water body into which these wastes are disposed. Little work has been done in connection with defining the properties of negative buoyant plumes, and the work which has been reported has dealt primarily with cloud formation and atmospheric conditions.

Until recent years, the problems associated with the disposal of dense wastes has, by its very nature, gone unnoticed. These dense wastes have settled to the bottom of the streams and caused no aesthetic problem. It is obvious that the effects on bottom dwelling organisms could have been significant, yet virtually unnoticed. Since the recent enactment of the water pollution control legislation, federal and state regulatory agencies have begun to require municipalities and industries to not only improve the degree of treatment of their wastes, but also to minimize the adverse effects which their effluents have on the receiving streams.

This study is currently being conducted in an effort to determine dispersion and mixing properties of negatively buoyant jets. The parameters which are being considered in this study are the densimetric Froude number of the channel flow, the densimetric Froude number of the jet, and the angle at which the waste is injected into the stream relative to the stream bed.

In this study, some meaningful relationship between the above parameters and mixing properties of dense wastes will be sought. It is hoped that answers can be found to such questions as: Does the angle at which the waste is introduced into the stream affect the distance required to attain mixed conditions; does it affect the rate of settling of the dense waste? What is the effect of density differences between the waste and the receiving water?, etc.

The basic equipment used in this study consisted of a channel, a manifold and injection system, and the detection and recording instruments.

The flume used in this investigation was a rectangular steel channel sixty feet long, two feet wide, and one foot deep. The channel walls

consisted of glass panels and the bottom was painted with epoxy paint to resist chemical corrosion. The entire system was supported at two points, one of which has a mechanical screw jack mechanism for changing the channel slope. Several types of steel gratings are available to give the channel bottom the desired roughness characteristics. It was found that the use of any roughness mats caused inordinate turbulence, consequently, no mats were used. For these experiments the channel slope was adjusted to the horizontal position. An adjustable height weir was installed at the downstream end of the flume to provide a means for controlling depth of flow. When installing the gate, a space was left under the gate which permitted the dense salt water to flow under the structure and prevented the buildup of a salt-water wedge upstream from the overflow gate. Such a wedge would have interfered with the mixing of the salt water from the diffuser and would have prevented the establishment of a meaningful steady state condition.

The system for injecting the salt water into the channel consisted of a mixing tank from which the solution was pumped through a flow meter to the diffuser. The diffuser consisted of a piece of one-half inch inside diameter pipe with seven equally spaced one-eighth inch diameter holes. The salt solution which was injected into the flowing water in the channel also contained pontacyl pink dye so that visual observations of its dispersion could be made. However, for analytical purposes, the dispersion of the salt solution was determined by measuring the conductance of the mixed solution in the flume. These measurements were taken in cross-sections at two foot intervals downstream from the diffuser for a distance of twenty-four feet. A total of nine point measurements were

taken in each of these cross-sections. These were at the quarter points in the vertical and in the horizontal.

The following parameter variations are being considered: The channel velocity, ranging from 0.07 feet per second to 0.13 feet per second; the ratio of the density of the injected salt water to the density of the water flowing in the channel, ranging from 1.0068 to 1.0170; and the angle at which the salt solution is injected into the channel. The jets were directed vertically and also at 45° either side of the vertical.

A detailed analysis of the data thus far collected is presently underway and a complete report will be prepared subsequently. A preliminary analysis of the data indicates that most of the mixing occurs very rapidly within the first few hundred jet diameters from the diffuser and that no appreciable dispersion or settling takes place at more than about a thousand diameters downstream. It is apparent that the angle at which the solution is injected does influence the dispersion.

It is believed that, in the future, more emphasis will be placed upon the disposal of dense wastes in flowing streams. Because of this and the fact that so little work has been done on the subject in the past, it is felt that further investigation of this subject is justified and highly desirable. This investigation could be expanded to include such features as more complex diffuser designs, conditions which produced interflow in a stratified stream, and others.

WATER QUALITY CHANGES IN A NEWLY CONSTRUCTED RESERVOIR

Faculty Investigator: Frank L. Parker

Research Assistant: John C. Burdick

Project Support: Corps of Engineers
Vanderbilt University

Project Began: March, 1968

Scheduled Completion: December, 1969

Critique:

Burdick has estimated the water quality changes to be expected in a newly constructed impounding reservoir based upon preimpoundment and laboratory data. This work was sponsored by the U. S. Army Corps of Engineers under its Graduate Fellowship Program. A Ph.D. thesis based upon this work is currently in preparation and will be a subsequently published report of the Corps of Engineers.

Preimpoundment information was collected in order to define the prevailing conditions of climate, streamflow, and water quality at the proposed reservoir site. The morphometric parameters of the new reservoir were defined from the project design plans of the Corps of Engineers. Laboratory studies were conducted to determine the behavior of representative soil and vegetation samples when stored in lake water under either aerobic or anaerobic conditions. These studies were concerned with the oxygen consumption properties of the samples as well as with their potential in supplying iron, manganese, nitrogen, and phosphorous to the reservoir system.

Since the seasonal thermal structure is the primary determinant of water quality of a reservoir both from the aspect of the development of stratification and because of the influence of temperature on chemical reaction rates, the first step of the analysis was concerned with the prediction of temperature changes in the reservoir. A simple generalized model was developed to estimate the seasonal thermal regime of the reservoir employing equilibrium temperatures and thermal exchange coefficients based upon past climatological records. The estimated temperature distribution with depth and time showed agreement with the observed temperature distribution which was adequate for the purposes of this study.

Successive phases of this analysis will involve an estimation of the effects of the inundated soils and vegetation upon the oxygen resources of the reservoir determined from the laboratory studies and the predicted temperature conditions. Following this, estimated levels of iron, manganese, phosphate, and nitrogen compounds will be proposed based upon knowledge of the preimpoundment water quality, the estimated seasonal temperature and oxygen conditions in the reservoir, and the information determined from the laboratory studies.

During the course of this investigation, the reservoir under study was completed, and it was possible to make field measurements of the water quality parameters of interest covering the period of the first year of reservoir impoundment. Upon completion of the analysis of the data, the estimated values will be compared with the actual observations to indicate the degree of reliability of the techniques employed.

At present, the laboratory and field investigations have been completed and the analysis and formulation of the final report are in progress. Publication of this work is anticipated this year.

IMMOBILIZATION OF PHOSPHORUS IN BOTTOM SEDIMENTS

Faculty Investigator: Frank L. Parker
Research Assistant: Jerry Anderson
Project Support: Vanderbilt University
Project Began: July, 1968
Scheduled Completion: June, 1970

Critique:

The amount of nutrients added to our receiving streams and impoundments is constantly increasing. As a result, the pressure to stop completely or control this menace of eutrophication in our lakes and streams has also increased. Engineers and scientists have responded by improved methods for removal of phosphates from domestic sewage by making in-plant changes or by adding new treatment methods. Hall and Engelbrecht (1) have reported on various techniques, including chemical precipitation and coagulation, for the removal of phosphorus from sewage. Owen (2) reported that tertiary treatment with lime would reduce the phosphorus concentration by 99 percent or more. However, the sludge produced was difficult to dewater and the chemical costs were quite high. Another process that was tried was a combination of chemical and biological treatment. Utilization of this method yielded phosphorus residuals of less than 0.1 mg per L. (3)

However, even with new techniques to reduce the phosphorus concentrations in domestic waste effluents, we are only reducing one source of phosphorus. The exchange pattern that occurs in our receiving streams

is well recognized but insufficient knowledge exists concerning it. Figure 1 gives a simplified idea of the equilibrium. Figure 1 illustrates the equilibrium system between the bottom muds (solid phase) and lake water (liquid phase). This equilibrium was recognized by Hayes and Phillips (4) as a dynamic equilibrium represented as

Phosphorus in aqueous phase $\leftrightarrow$ Phosphorus in solid phase
 (a small fraction of the whole) $\rightarrow$ (a large fraction of the whole)

Therefore, one can see that a potential sink for the phosphorus is in the bottom muds of a reservoir. The radioactive tracer technique (Hayes and Phillips) made it possible to measure the turnover time. The turnover time gives no indication of how much phosphorus was deposited to the bottom soils but did show that an exchange pattern did exist.

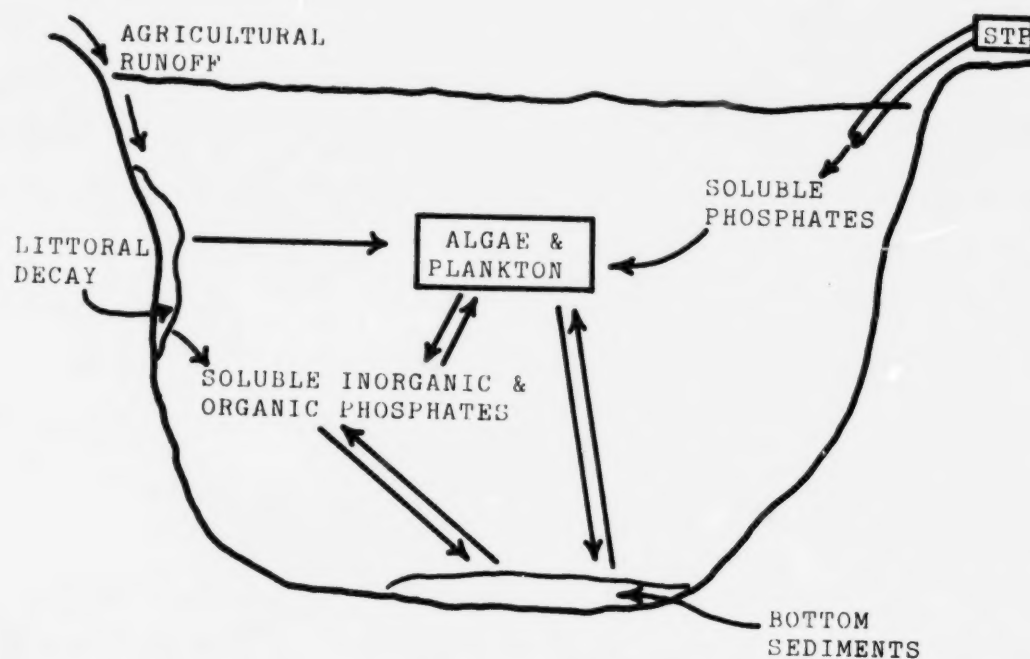


FIGURE 1 - MUD-WATER EQUILIBRIUM

Since this exchange takes place, one could possibly assume that the phosphorus could be fixed in the bottom muds as an insoluble precipitate. By diligent addition of Ca^{++} in the form of $\text{Ca}(\text{OH})_2$ or CaCl_2 , one might expect to form insoluble hydroxyapatite. Therefore, laboratory experiments have been designed to determine the optimum amount of calcium needed to be added to the overlying water to precipitate a known concentration of phosphorus at a constant pH. The objective of this research will be to see if an addition of Ca^{++} to the upper region of the overlying waters will precipitate the soluble phosphorus. After equilibration, it will be determined if the phosphorus that was precipitated will remain fixed or bound in the soil such that there will be no dissolutions. In essence, how good is the bottom soil as a sink for an insoluble phosphate precipitate? This will be done in two phases: (1) Holding various concentrations of calcium constant for various phosphorus concentrations over a range of constant pH; and (2) Holding phosphorus concentrations constant while varying concentrations of calcium over a range of constant pH. The bottom sediment consists of a natural soil taken from an area about 2 miles below J. Percy Priest dam. In addition, other clays, illite, kaolinite, and montmorillonite have been selected as controls. It is hoped that the studies on the control clays will enable one to predict the amount of Ca^{++} needed for a natural soil whose clay content has been determined. After the treated waters have reached equilibrium, the water will be leached through the soil to determine the effectiveness of each soil on the retention or fixation of the phosphate. After the treated water has been completely leached, a sample of water from J. Percy Priest Lake will then be placed in a column above the soil to measure any dissolution of the

phosphorus. It is intended at this time to measure the reaction constants for the precipitation of the phosphorus with calcium, and to compare the residual calcium and phosphorus concentration at the pH under study to that predicted by the solubility criteria for hydroxyapatite.

REFERENCES

1. Hall, M. W., and Engelbrecht, R. S., "Phosphorus Removal - Past, Present, and Future," Water and Waste Engineering, Volume 6, No. 8, 1969.
2. Owen R., Sewage and Industrial Waste, 25:5, 1953.
3. Tenney, M. W., and Stumm, W. J., Journal of Water Pollution Control Federation, Volume 35, No. 10, 1965.
4. Hayes, F. R., and Phillips, J. E., "IV - Radiophosphorus Equilibrium with Muds, Plants, and Bacteria Under Oxidized and Reduced Conditions," Limnology and Oceanography, Volume 3, No. 4, 1958.

QUANTIFYING THE EFFECTS OF RATE OF TEMPERATURE CHANGE ON THE BIOTA

Faculty Investigator: Peter A. Krenkel

Research Assistant: James Speakman

Project Support: Sport Fishing Institute
Vanderbilt University

Project Began: June, 1969

Scheduled Completion: December, 1969

Critique:

Background Justification

Two basic types of laboratory experiments concerned with the direct effects of temperature on aquatic organisms have been previously utilized (Collins, 1956). The shock test demonstrates the effects of instantaneous temperature change, while the chronic test shows the temperature above which a particular species cannot live for extended time periods when the rate of temperature change is less than the rate of acclimatization.

These two types of temperature response tests represent the extremes of rate of temperature change, one instantaneous and the other extremely slow. In the natural environment, temperature fluctuations are rapid but not instantaneous and, therefore, neither of the above tests accurately describe the effects of those temperature stresses commonly experienced by aquatic organisms.

Modern electrical generating systems usually operate with hydro power in conjunction with steam generated power (Krenkel and Parker, 1969). Due to seasonal and diurnal changes in electrical requirements, steam plants demonstrate wide fluctuations in load.

Typical curves of river temperature below a steam plant demonstrating diurnal variation as much as 14.4°F have been presented by Gameson, et al. (1959). Alabaster (1963) points out that temperature maxima may be attained within a few hours, and although the maxima may not reach ultimate lethal levels, the rapid attainment of these maxima may kill fish.

Also, the temperature change below a peaking power hydroelectric plant during periods of low flow may be as much as 18°F within a few hours with a corresponding flow rate change of 8000 cfs according to Krenkel, et al. (1965). The Tennessee stream pollution control board has reported several fish kills caused by this rapid change of temperature (Jones, 1966). Brett states that rapidly onsetting low temperatures can constitute one of the greatest threats to survival when fish are accustomed to relatively warm water because of the inherent slow rate of acclimatization to low temperatures (Brett, 1960).

Statement of Problem and Specific Objectives

Introduction - The recent Water Quality Standards Hearings have dramatized the paucity of usable data available that will allow rational stipulation of temperature standards that will protect the biota. A major source of contention has been centered around the allowable rate of temperature change that will not adversely affect aquatic life. The literature describing the effects of "shock loading" of temperature on the biota is quite sparse.

For example, recent recommendations from the State of New York limit the rates of change to 2°F per hour for freshwater and 1°F per hour for saline water. The State of Tennessee has proposed a 3°F per hour maximum

change. European workers have stated that a 5°C change can completely transform a water milieu and a 1°C change can have adverse consequences on the biota. Typical of data substantiating these numbers is that of Ruth Patrick (1953), where she states that "it is a well known fact that a sudden change in temperature of more than 2° is harmful to the sunfish."

The lack of data then, appears to give some credence to those objecting to the establishment of rate of change of temperature standards, even though the lack of such standards would be unreasonable.

Perusal of the literature also demonstrates that little knowledge is available on the sub-lethal effects of temperature change. It is quite obvious that even though an organism may not die, damage to its reproductive facilities, for example, cannot be tolerated.

A mathematical description of the rate of change of temperature that would not cause adverse effects on the biota is mandatory, if rational stream temperature standards are to be promulgated.

Objectives - In view of the previous statements, it is logical that the specific objectives of the proposed investigation be as follows:

1. To derive and substantiate a mathematical model describing rate of temperature change that will yield a usable, quantitative number for water quality criteria.
2. To establish sub-lethal and lethal rate of temperature changes in accord with objective one.
3. To utilize suitable biochemical changes in the organisms to describe sublethal effects and utilize conventional statistical methods to determine lethal effects.

4. Utilizing the results of objectives 1, 2, and 3; determine the proper "application factor" that will state rate of change of temperature in terms of that rate constant that will produce no adverse change in the organism in question.

Methodology - It is the purpose of this study to establish a procedure analogous to the routine bioassay procedure which will allow the quantitative study of acute and sublethal effects of rapid environmental temperature changes.

The test animals, Bluegill (*Lepomis macrochirus*), were ones typical of the Tennessee Valley, and were obtained from local hatcheries.

The test animals are being acclimatized at temperatures ranging from 5°C to 25°C at 5°C increments.

After sufficient acclimatization, a number of test specimens from each acclimatization temperature will be subjected to various short term temperature stresses. The two types of change which have been selected for study are:

A. Zero Order Rate (Constant rate of change). Such a rate is the simplest in mathematical form. It can be expressed:

$$\frac{d\theta}{dt} = K$$

where

θ = Temperature at time (t)

t = Time

K = Rate constant, the parameter which defines the severity of the rate of change. It can be positive or negative for heating or cooling respectively.

Values of K will range between a value which will cause 100% mortality in

the two-hour test period and one which will produce no significant statistical sublethal response.

B. First Order Rate. The first order rate of temperature change can be expressed mathematically as:

$$\frac{d\theta}{dt} = K\theta$$

where

θ , t , and K = Defined in previous equation

The first order rate of change more nearly approximates the natural change induced in streams by thermal pollution sources mentioned herein.

The various temperature changes will be induced by a previously programmed controller equipped with a recorder which continuously records actual aquarium temperature. The acclimatization temperatures will be maintained using constant-temperature water baths.

The order of tests will be from the highest rate constant to the lowest one. At the highest rate constant utilized, all test specimens will have been killed within the two-hour test period by the temperature stress. In each succeeding test, the rate constant will be reduced until a spectrum of rate constants and related percent survival data is collected, ranging from 0% survival to 100% survival. This data will be plotted on arithmetic-probability graph paper in the same manner as in chemical toxicity bioassays.

Previous Work Performed in this Field - During the months of June thru August of 1967, a preliminary study was conducted, in which the methodology for the proposed research was developed. The rather simple system consisted primarily of a constant elevated temperature (39.2°C)

water bath which served as a source of heat. The test chambers which held the Bluegill Sunfish test specimens were 5-gallon glass jars which were placed in the water bath at the beginning of each stress period. These jars had been maintained at room temperature for at least 4 weeks to assure acclimatization of the organisms. The only acclimatization temperature utilized was that of room temperature (approximately 23°C) which fluctuated as much as 3°C as a result of climatic conditions.

In order to induce the temperature rise, the cool test chamber was placed inside the high temperature water bath, and thru natural heat conduction and convection, the temperature within the test chamber approached that of the water bath. In an ideal case, where all heat which is lost from the source is gained in the test chamber, a perfect first order rise will occur. That is:

$$\frac{d\theta}{dt} = -K (\theta_B - \theta)$$

where

θ = temperature at time t

θ_B = water bath temperature (39.2°C)

t = time

K = rate constant which depends on volume of water in the test chamber

However, due to loss of heat from both the test chamber and the water bath to the atmosphere, heat transfer lag thru the glass walls of the chamber, fluctuating initial temperature, incomplete mixing within the chamber, a first order temperature equation becomes only an approximate model of the true temperature rise in the chamber.

After two hours of induced temperature rise in separate experiments,

the volume of water within the test chamber was increased or decreased. An increased volume within the test chamber decreased the rate of temperature rise and vice versa.

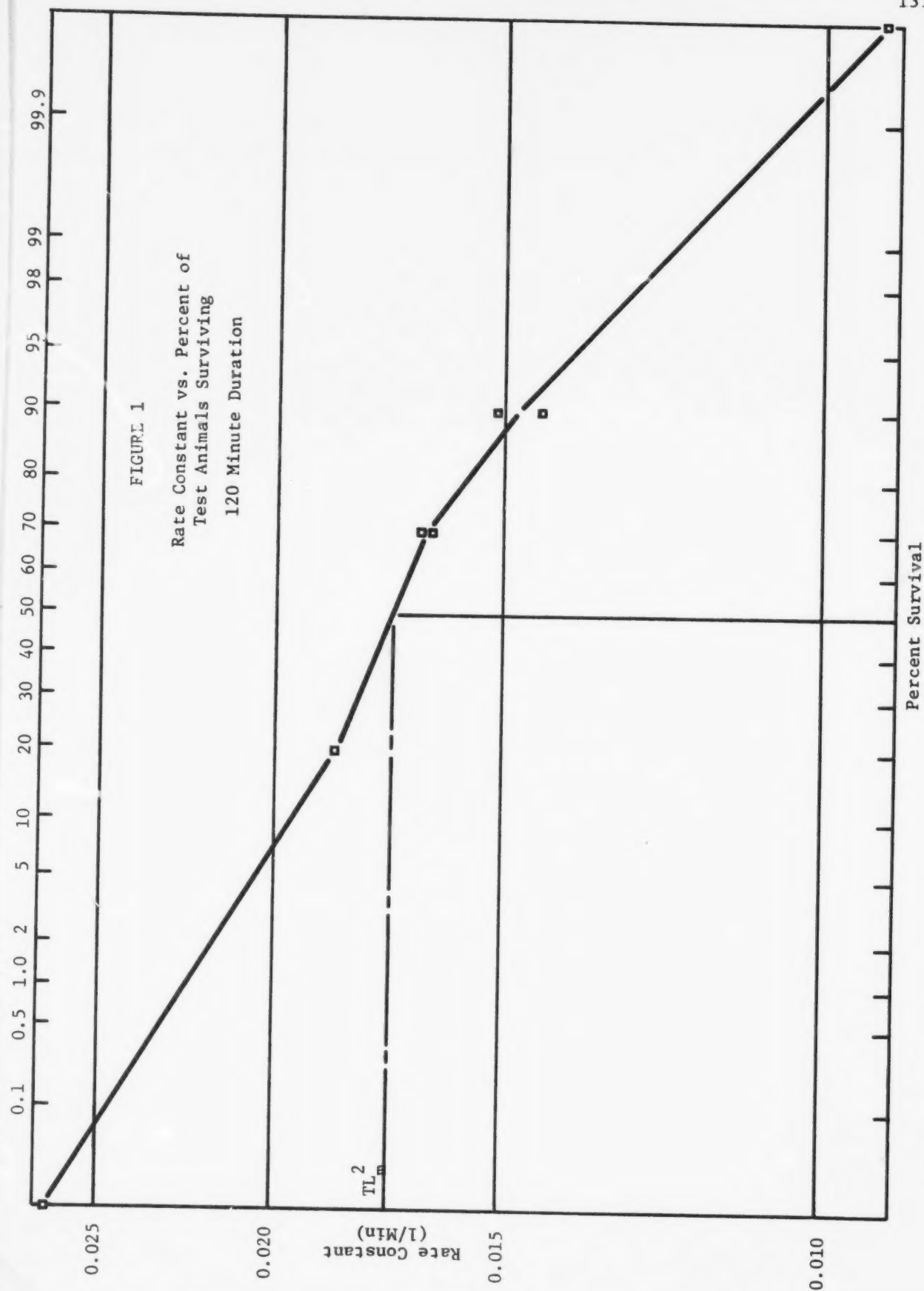
By running a number of experiments with various volumes of water within the test chamber, a spectrum of 1% survival data and approximate rate constants (K) was determined relating to the approximate acclimatization temperature.

These data were plotted on logarithmic-probability graph paper in a manner similar to that used in chemical bioassays, and a mean value was found to be 0.018 min.^{-1} . Considering the variation from a truly first order temperature rise, the statistical relationship between rate constant and % survival is exceptionally good, as is shown in Figure 1.

The mean value, then, was called the TL_m^2 for a first order temperature rise and an acclimatization temperature of approximately 23°C .

It should be noted that the preliminary study was conducted primarily to develop the methodology and feasibility for a more extensive study. Obviously this preliminary study did not account for the dependence of mean tolerance limits on acclimatization temperature. Also, some of the final temperatures exceeded the upper lethal limits while others did not, and, therefore, the lethal temperature may have become a factor.

The limitations of these initial studies were a result of inadequate instrumentation and environmental control. Obviously, the investigation described herein will be conducted using closely controlled environmental conditions and programmed acclimatization of the test organisms.



REFERENCES

1. Cairns, John Jr., "The Effects of Heat on Fish," Industrial Wastes, May - June, 1956, pp. 180-183.
2. Krenkel, P. A., and F. L. Parker, "Engineering Aspects, Sources and Magnitude of Thermal Pollution," National Symposium on Thermal Pollution, Portland, Oregon, Vanderbilt University Press, Nashville, Tennessee. (In press)
3. Gameson, A. L. H., Gibbs, J. W., Barrett, M. J., "A Preliminary Study of a Heated River," Water and Water Engineering, January, 1959.
4. Alabaster, J. A., "The Effect of Heated Effluents on Fish," Journal, Air and Water Pollution, Vol. 7, No. 3, 1963.
5. Krenkel, P. A., Cawley, W. A., Minch, V. A., "The Effect of Reservoirs on Waste Assimilative Capacity," Journal, Water Pollution Control Federation, September, 1965.
6. Jones, S. L. Personal Communication, 1966.
7. Brett, J. R., "Thermal Requirements of Fish - Three Decades of Study, 1940-70," Technical Report W 60-3, U. S. Department of the Interior, 1960.
8. Patrick, R., "Aquatic Organisms as An Aid in Solving Waste Disposal Problems," Sewage and Industrial Wastes Journal, February, 1953.
9. Schafer, R. D., "Variations in Free Amino Acid Composition in Some Marine Invertebrates Subjected to Specific Types of Pollutants," Rev. Intern. Oceanogr. Med. Tome X, 1968.
10. Jeffries, Harry P., "Chemical Responses by Marine Organisms to Stress, Phase 1.," Technical Report No. 1, Graduate School of Oceanography, University of Rhode Island.

11. Fujiya, Masaru, "Use of Electrophoretic Serum Separation in Fish Studies," Journal, Water Pollution Control Federation, Vol. 33, p. 250.
12. Anon., "Thermal Pollution of Water," Sport Fisheries Inst. Bull. #191, January-February, 1968.
13. Mount, D. I., "Developing Thermal Requirements for Freshwater Fishes," Proceedings, National Symposium on Thermal Pollution, Biological Considerations, Federal Water Pollution Control Administration and Vanderbilt University, Portland, Oregon, 1968.
14. Cocking, A. W., "The Effects of High Temperatures on Roach, *Rutilus rutilus*, II. The Effects of Temperature Increasing at a Constant Rate," Journal of Experimental Biology, March, 1959.
15. Cocking A. W., "The Effects of High Temperatures on Roach, I. The Effects of Constant High Temperatures," Journal, Experimental Biology, March, 1959.
16. Anon., "Aquatic Life Water Quality Criteria," 2nd Progress Report, ORSANCO, Journal, Sewage and Industrial Wastes, May, 1956.
17. Threinen, C. W., "Cause of a Midsummer Plant of Rainbow Trout in a Southern Wisconsin Lake, with Notes on Acclimation and Lethal Temperatures," Progressive Fish Culturist, January, 1958.
18. Bardach, J. E., Bjorklund, R. G., "The Temperature Sensitivity of Some American Freshwater Fishes," The American Naturalist, July-August, 1957.

PROPOSED WORK

INTRODUCTION

Even though this has been the first year since the establishment of the center, it is thought that significant progress has been made. The concept of concentration of talent and resources for research and training in the subject area is unquestionably good, inasmuch as both research and training have benefited.

The investigations pursued have yielded results that are of value to water pollution control activities, and have simultaneously assisted in the training of competent water quality engineers, well versed in both water quality management and hydraulics and hydrology.

The value of the information retrieval operation is unquestionable, inasmuch as we are rapidly becoming known as a source of information in this discipline. The following description of proposed research endeavors includes continued support of this aspect of the center as described in a previous section.

TEMPERATURE DISTRIBUTIONS RESULTING FROM
COOLING WATER DISCHARGES

Faculty Investigator: P. A. Krenkel, F. L. Parker
Research Assistant: E. M. Polk
Project Support: Center Grant
Project Began: October 1968
Scheduled Completion: October 1970

Critique:

The preceding year's work in this area has already been described in the section on research accomplishments. A portion of the comments on expected work is repeated.

Additional temperature distribution data for both the mixing and stratified cases is necessary to adequately test proposed distribution models or develop new ones. At least two of the steam plant sites previously studied, Johnsonville and Bull Run, are known to exhibit temperature distributions in both the mixing and stratified categories depending upon flow levels in the receiving reservoir. A resurvey of these sites will be scheduled when hydraulic conditions indicate a preferred type of temperature distribution. Also, to gather additional data for the conservative, mixing type distribution, two new sites, John Sevier and Petersburg, are proposed for study this year.

To date, no attempt by Vanderbilt has been made to gather data specifically for the purpose of studying the non-conservative (heat loss) type of temperature distribution. The lack of thermo-electric plants in the Tennessee area, which create a 10°F or higher mixed temperature rise in the receiving stream, is the primary reason for the avoidance of this type of study. However, with the acquisition of new monitoring equipment to allow rapid measurement of water temperature and meteorological variables, a number of sites in the Southeast are now being considered for study to evaluate heat dissipation by cooling. Letters of inquiry have been sent to a total of thirteen thermal-electric generating plants in the states of Mississippi, Georgia, Alabama, South Carolina, North Carolina, West Virginia, Pennsylvania, and Virginia. Information obtained from the replies to the inquiries will be used to pick sites that should yield useful field data.

The field work will be scheduled to include a variety of site geometries, river flow conditions, and meteorological conditions. Theoretical work has been proceeding on wedges, jets, and diffusion models. This work will continue as indicated in the respective sections of this progress report. The field data will enable evaluation of the mathematical models and provide guidelines for improving them.

In addition to the field work, which requires large amounts of time and money, preliminary calculations are being prepared for possible lab studies. The adequacy of present facilities is being evaluated. Laboratory studies could provide larger volumes of data under controlled conditions. Such parameters as entrainment coefficients, critical Froude numbers, and jet drag coefficients could be evaluated in this way. Field

data will of course still be necessary as a final verification.

EFFECT OF GEOGRAPHICAL LOCATION ON COOLING POND
REQUIREMENTS AND PERFORMANCE

Faculty Investigator: Edward L. Thackston
Research Assistant: Larry Elliot
Project Support: Center Grant
Project Began: May 1969
Scheduled Completion: June 1970

Critique:

The preliminary results have been reported in the section on research accomplishments. Reference is made to that section for detailed comments. The following is excerpted concerning the work to be completed.

ANALYSIS OF RESULTS

Since the calculations for this project have not been completed, only a short discussion of how the results will be summarized and presented is appropriate.

It is planned to summarize the results as a series of maps of the U. S., one map for each of several possible parameters of interest, with lines connecting points of equal values of the parameter, similar to

isotherms. Some of the possible parameters which might be presented in this fashion are listed below.

- (1) Highest equilibrium temperature during the year.
- (2) Lowest equilibrium temperature during the year.
- (3) Date on which rising equilibrium temperature passes through a particular temperature, such as a representative fish spawning temperature, in the spring.
- (4) Length of time equilibrium temperature stays above a certain value during the summer.
- (5) Maximum equilibrium temperature for critical conditions.
- (6) Maximum heat exchange coefficient during the year.
- (7) Minimum heat exchange coefficient during the year.
- (8) Net plant temperature rise for a 1500-acre pond, for June.
- (9) Net plant temperature rise for a 1500-acre pond, for June, critical conditions.
- (10) Pond size necessary to produce 50 percent cooling (7.5°F), for June.
- (11) Pond size necessary to produce 50 percent cooling (7.5°F), for June, critical conditions.

There are many other parameters, some only slight variations of those listed above and some quite different, which could be mapped. Those parameters which have significant variations and a logical enough pattern throughout the country to allow presentation on such a map will be plotted.

DISCHARGE OF NEGATIVELY BUOYANT FLUIDS

Faculty Investigator: F. L. Parker, B. A. Benedict
Research Assistant: Rick Conner
Project Support: University
Project Began: July 1969
Scheduled Completion: September 1971

Critique:

In an earlier section, it was reported that Connor had been studying, experimentally, the problem of discharge of a fluid heavier than the ambient receiving fluid. It is proposed to extend this work in the coming year to provide data for a wider range of conditions.

Parameters to be more comprehensively treated include the river densimetric Froude number; the jet densimetric Froude number; the jet angle with the vertical; the number, size and spacing of the jet ports. These parameters can be varied by changing jet velocities, jet densities, and flume flow. Consideration will be also given to field measurements to substantiate and amplify laboratory findings.

There are other effects which will be considered. One is the effect of pre-existing density stratification in the receiving fluid, specifically where the jet fluid has a density intermediate between the denser bottom layer and an upper layer. This situation is precisely that encountered where cooling water is discharged to a stratified flowing

fluid and is hence of value for discharges of chemical wastes or heated discharges. For this reason, work on this problem would be also coordinated with the ongoing thermal studies.

The height of rise as a function of jet velocity (and angle) will be related to depth of flow to observe free surface effects of mixing.

Among the items of ultimate interest is the definition of the distance required for attainment of a uniformly mixed profile. Those conditions most conducive to such mixing will be sought, as well as defining situations wherein complete mixing does not occur, e.g., in a layer along the bottom. Preliminary data indicates that the data net may have to be increased near the jets and near the bottom (compared to Connors' net) to adequately define the movement of the jet material. If the initial jet momentum is insufficient to provide uniform mixing, downstream sections will be observed to detect further mixing due to dispersion and turbulent diffusion. Little work has been done in defining diffusion parameters in those cases where density differences exist; this shortcoming also exists for treatment of heated discharges.

Concurrent with data collection and analysis, efforts will be made to use principles of fluid mechanics and mixing processes for establishing mathematical models. Turner (1966), Morton (1959), and Cederwall (1967) have considered discharges of denser fluids, but not with a moving ambient fluid. For the multi-jet problem, it is likely that an approach such as that of Brooks and Koh (1965) may be used. Treating discharges of lighter fluids, it was suggested that at some distance the jets could be considered to act as a line source, rather than a series of point sources.

LIST OF REFERENCES

1. Brooks, N.H., and R. C. Y. Koh, "Discharge of Sewage Effluent from a Line Source into a Stratified Ocean", XIth Congress, International Association for Hydraulic Research, Leningrad, 1965.
2. Cederwall, K., "Jet Diffusion: Review of Model Testing and Comparison with Theory", Report, Hydraulics Division, Chalmers Institute of Technology, Goteburg, Sweden, February, 1967.
3. Morton, B. R., "Forced Plumes", Journal of Fluid Mechanics, 5, 1, 151-163, January, 1959.
4. Turner, J. S., "Jets and Plumes with Negative or Reserving Buoyancy", Journal of Fluid Mechanics, 26, 4, 779-792, 1966.

TEMPERATURE INCREASES BELOW DAMS

Faculty Investigator: Edward L. Thackston

Research Assistant: Edward M. Polk

Project Support Center Grant

Project Began: August, 1969

Scheduled Completion: September, 1971

Critique:

Warming of Cold Discharges from Hydroplant

The heat budget, and the individual components in it, should be tested to see how it conforms to observations in rivers. This will be necessary before changes due to heat dispersion in analyzing mixing jets with complete assurance.

Heretofore, most of the tests of the heat budget have been on large lakes. A few studies have been reported on flowing streams, but the studies have not been complete enough or general enough to allow complete verification. The eventual objective should be calculation of heat transfer rates based on standard data from a nearby weather station. Most reported studies have measured variables on the water, such as radiation, which are not always available at study sites. Also, the transposability of data from weather stations to nearby streams has not been investigated.

There are few sites at steam plants where the mixed river temperature is sufficiently above equilibrium to provide heat transfer rates which can be measured accurately. However, there are several hydroplants where

the discharge temperature during the summer is as much as 40°F below equilibrium temperature. This should provide a fruitful opportunity for study, since the heat transfer mechanisms are essentially the same for heating and cooling.

The site tentatively chosen for next year's preliminary study is the Cumberland River, below Wolf Creek Dam in south-central Kentucky. There is approximately 80 miles of open river below the dam to the first major tributary, and the outflow stays below 50°F all summer.

It is proposed to tag a slug of cold water within a fairly uniform discharge and follow it downstream for two days with drifting boats carrying weather equipment. The temperature of the water will be measured continuously and compared with predicted values computed from the measured weather data. A fluorometer mounted on one of the boats will be used to locate and follow the center of the dye cloud used to identify the slug of water to be monitored. Weather instruments will also be placed on the bank nearby. Data from the nearest U. S. Weather Bureau station will be tested for its ability to predict the rate of warming of the water at the river.

The major problems will be variability in flowrate and depth of water due to operation of Wolf Creek Dam as a peaking power plant; shading of a portion of the river from solar radiation by bluffs and trees along the banks; modification of wind speeds by local topography; and navigation at night. We intend to arrange with TVA and the Corps of Engineers for an acceptably steady flow, but the other problems will have to be approached at the time the study is done.

HEAT TRANSFER IN FLOWING WATERS

Faculty Investigators: P. A. Krenkel, B. A. Benedict

Research Assistant: Vladimir Novotny

Scheduled to Begin: October 1969

Scheduled Completion: October 1971

Critique:

The mechanism of heat transfer in water bodies has recently received considerable attention. It has become apparent that relationships between the processes of heat transfer and turbulent mechanisms have not yet been established. Advection, diffusion, turbulent energy dissipation, and atmospheric heat exchange all contribute to the heat transfer phenomenon. It is particularly pertinent to investigate the equilibrium temperature relation expressed by Edinger and Geyer (1965) and shown below.

$$H' = K(T - T_e) \quad (1)$$

where H' = atmospheric heat transfer,
 K = heat exchange coefficient,
 T = temperature in stream,
 T_e = equilibrium temperature.

The question arises as to whether or not the intensity of turbulence

(especially at the air-water interface) influences the rate of thermal exchange between the water and atmosphere. Expected similarity to gas (oxygen, etc.) transfer research suggests some laboratory scale approaches to a study of K as influenced by turbulence. The following program of study will be instituted.

1. Conduct small scale studies in lab vessels, as performed by Holley (1969) and Krenkel and Orlob (1962) for gas transfer studies. Here, as in the latter study, a stirrer in the vessel will be run at progressively higher speeds and the variation of rate of heat transfer noted. It is expected that the heat transfer will be independent of stirrer speed (induced turbulence) below some plateau level; above this plateau, a dependence would be expected.

2. After adequate information from vessel-scale testing, perform experiments in a flume. The flume to be used is 60 feet long by 2 feet wide and can be run as a once-through or as a recirculating flume. Radiation should be small over this length, thus can be neglected. Experience from gas transfer studies (Krenkel and Orlob, 1962) implies that heat transfer should attain measureable magnitudes in this length. Therefore, if the heat gain due to turbulent energy dissipation is small, significant data should be attainable for evaluation of the influence of turbulence on the heat exchange coefficient.

Particularly significant to this study is the availability of Mr. Vladimir Novotny, who is with the hydraulic laboratory in Brno, Czechoslovakia, and presently studying for his Ph.D. degree at Vanderbilt University. His knowledge of the Eastern European literature in this area will prove invaluable. For example, the relationships developed by the

Russians between mass transfer and various turbulence parameters are relatively unknown in this country (Levich, 1962).

LIST OF REFERENCES

1. Edinger, J. E., and J. C. Geyer, "Heat Exchange in the Environment", Cooling Water Studies for Edison Electric Institute by Johns Hopkins University, Baltimore, 1965.
2. Holley, E. R., Jr., "Some Data on Diffusion and Turbulence in Relation to Reaeration", Research Report No. 21, University of Illinois Water Resources Center, July, 1969, 53 pp.
3. Krenkel, P. A., and G. T. Orlob, "Turbulent Diffusion and the Reaeration Coefficient", Journal of the Sanitary Engineering Division, American Society of Civil Engineers, 88, SA2, 53-83, March, 1962.
4. Levich, V. C., "Physicochemical Hydrodynamics" Prentice-Hall, Inc. 1962.

SEPARATION OF SOLAR AND HEATED DISCHARGE EFFECTS

Faculty Investigator: Edward L. Thackston

Project Support: Center Grant

Scheduled Beginning: January, 1970

Scheduled Completion: September, 1971

Critique:

It sometimes happens that condensor cooling water discharges onto slightly submerged mud, or under certain river conditions, flows into such an area. In such instances it becomes difficult to determine that part of the temperature rise due to solar radiation and that part due to the heated discharge. Where solar heating is significant, the measured cross-sectional temperature distributions may give a mistaken impression of the movement of the heated discharge. It would be beneficial to the analysis of induced temperature rises if these effects could be separated; then the effect of the heated effluent on the pre-existing natural state could be evaluated.

Three approaches have been considered:

1. During the test observations, continuous monitoring of the temperature at a nearby point similar to the discharge area but unaffected by the heated discharge. These rises would then be "subtracted" from the temperature of the area affected by the discharge.

2. Perform simultaneous dye and temperature studies thus enabling determination of the path of the heated effluent. Determination of the quantity of heat due to the discharge is then possible.

3. From a knowledge of the meteorological conditions at the site, calculate the expected temperatures due solely to such sources. Then, again, "subtract" these temperature rises from measured values to evaluate the effect due only to cooling water discharge.

Of these three, dye studies would be the most expensive (manpower and money). It is therefore expected that the other two approaches will be tried first. The goal is to provide some realistic guidelines both for prediction and for evaluation of existing conditions.

MASS AND HEAT TRANSFER ACROSS DENSITY DISCONTINUITIES

Faculty Investigator: Frank L. Parker
Barry A. Benedict

Project Support: Center Grant

Scheduled Beginning: January, 1970

Scheduled Completion: September, 1972

Critique:

When cooling water is taken from the hypolimnion of deep reservoirs, it is possible during the summer that the heated discharges will still be cooler than the surface waters. In that case, the cooling waters would move as an interflow. Very little work has been done on mass transfer across such boundaries and even less work on heat transfer across such boundaries. Since the rate of mass and heat transfer profoundly affects the rate of heat dissipation, the problem is of considerable importance. It is proposed to undertake simple laboratory experiments with a small model simulating stagnant water in a reservoir first to determine mass and heat transfer rates. After this work is underway, the efflux velocity of the cooling water stream will be introduced. Finally, currents in the ambient fluid will be initiated. Parallel to this development of a physical model will be the start of a mathematical model.